CRESCENT CREEK AND LITTLE DESCHUTES RIVER HYDROLOGY STUDY

Prepared for:
Deschutes Basin Board of Control, and
City of Prineville, Oregon

Prepared by:
R2 Resource Consultants, Inc. and
Biota Pacific Environmental Sciences, Inc.

November 2016

Crescent Creek and Little Deschutes River Hydrology Study

Prepared for:

Deschutes Basin Board of Control
P. O. Box 919
Madras, Oregon 97741

City of Prineville
387 NE Third Street
Prineville, Oregon 97754

Prepared by:

R2 Resource Consultants, Inc.
15250 NE 95th Street
Redmond, Washington 98052

Biota Pacific Environmental Sciences, Inc.
P. O. Box 158
Bothell, Washington 98041

November 2016

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Summary

Eight central Oregon irrigation districts (Arnold, Central Oregon, Lone Pine, North Unit, Ochoco, Swalley, Three Sisters, and Tumalo; collectively the Irrigation Districts) and the City of Prineville, Oregon (City) are seeking Federal Endangered Species Act (ESA) incidental take permits for five species that occur or could occur on lands affected by Iirrigation District and City activities. As required by Section 10 of the ESA, the Irrigation Districts and the City (collectively the Applicants) are preparing the Deschutes Basin Habitat Conservation Plan (DBHCP) to minimize and mitigate the effects of the proposed incidental take on the covered species. The DBHCP is being prepared in cooperation with a multi-stakeholder Working Group representing the U. S. Fish and Wildlife Service (USFWS), National Marine Fisheries Service (NMFS), U. S. Bureau of Reclamation (Reclamation), U. S. Bureau of Land Management (BLM), Oregon Department of Fish and Wildlife (ODFW), Oregon Department of Environmental Quality (ODEQ), Oregon Water Resources Department (OWRD), the Confederated Tribes of the Warm Springs, Crook County, and several non-governmental entities.

One of the five species to be covered by the DBHCP is the Oregon spotted frog (*Rana pretiosa*), which was recently listed under the ESA as threatened. According to the USFWS (2014) the Oregon spotted frog may be affected by irrigation activities such as surface water storage, release, conveyance and diversion. The Oregon spotted frog is known to reside in portions of Crescent Creek and the Little Deschutes River, where it may be influenced by the storage and release of water from Crescent Lake Reservoir. This study provides background information of the hydrological influence of Crescent Lake Reservoir on Crescent Creek and the Little Deschutes River. It will be used, along with other ongoing studies of Oregon spotted frog breeding in these waters, to evaluate potential future reservoir operating regimes for the DBHCP.

Regulation of flows in Crescent Creek began in 1922 when a timber crib dam was built across the outlet of Crescent Lake. The active storage capacity of this reservoir was initially 86,900 acre-feet. Gradual deterioration of timbering and fill reduced the active storage capacity of the reservoir over time, necessitating the construction of a new earthfill dam with a length of 450 feet and a height of 40 feet in 1956 to restore the full 86,900 acre-feet storage capacity. The outlet works conduit at the current dam has a capacity of 1,325 cfs, and there is a 45-foot wide uncontrolled spillway in a saddle on the right abutment.

The purpose of this study is to quantify the influence of Crescent Lake Reservoir operations on flows in lower Crescent Creek and the Little Deschutes River. The relative contribution of flows in Upper Crescent Creek (above Crescent Dam) to flows in lower Crescent Creek and the Little Deschutes River are compared on a long-term average basis. Unregulated flows in Crescent Creek and the Little Deschutes River are compared to regulated flows on a daily basis.

Daily storage records are available from the U. S. Bureau of Reclamation (Reclamation) for Crescent Lake Reservoir for Calendar Years 1983 through 2015 (Reclamation 2016). This study is therefore focused on that 33-year period. Of those 33 years, the first 32 years (1983 through 2014) are considered representative of historical operations. Interim Operations were initiated in 2015 with a minimum year-round flow of 30 cfs in Crescent Creek below Crescent Dam. These two periods (historical and interim) are considered separately in this study.

Crescent Creek is a tributary to the Little Deschutes River. Crescent Lake Reservoir is located high in the Crescent Creek watershed at River Mile (RM) 29, where it captures only headwater runoff. The average outflow from Crescent Lake Reservoir is 54 cubic feet per second (cfs). The

largest tributary to Crescent Creek is Big Marsh Creek, which at times can double the flow in Crescent Creek where the two come together downstream of Crescent Dam. Between Crescent Dam and Big Marsh Creek, Crescent Creek also gains as much as 30 cfs from groundwater discharge (springs). From Big Marsh Creek to the mouth at the Little Deschutes River, Crescent Creek actually loses 1 to 2 cfs back to groundwater (USGS 2004). Approximately 57 miles downstream from its confluence with Crescent Creek, the Little Deschutes River joins the Deschutes River at RM 193. Crescent Dam is the only regulating structure in the Little Deschutes River Basin. The remainder of the basin is largely unregulated.

Surface water runoff in the Little Deschutes River Basin is heavily influenced by spring snowmelt, with high flows generally occurring in June and low flows at the end of summer. Surface runoff in the Little Deschutes River Basin is also influenced to some extent by interactions with groundwater. In contrast, surface water runoff in the remainder of the Upper Deschutes River Basin (upstream of Bend) is largely influenced by groundwater. Much of the precipitation in the Upper Deschutes Basin comes as snow, which is absorbed into the porous volcanic substrate upon melting and does not become surface water again until emerging from springs some distance downstream and up to several months later.

On a long-term average basis, the mean annual precipitation in a basin will be balanced by the sum of surface water outflow, evapotranspiration, and net groundwater exchange. The drainage area of Crescent Creek at the gage below Crescent Dam is 57 square miles and the mean annual precipitation is 60.1 inches (USGS 2016). This annual precipitation volume is equivalent to an average flow of 252 cfs. The mean annual evapotranspiration from the Upper Deschutes Basin is estimated to be 15 inches (USGS 2001), which is equivalent to an average flow of 63 cfs. The average flow in Crescent Creek below Crescent Dam is 48 cfs (equivalent to 11.4 inches). The average groundwater exchange upstream of Crescent Dam is therefore estimated to be a net loss of 141 cfs (equivalent to 33.7 inches) to groundwater. The ratio of groundwater loss to surface water outflow in Crescent Creek at Crescent Dam is 2.9.

The drainage area of the Little Deschutes River at La Pine is 859 square miles and the mean annual precipitation is 31.6 inches (USGS 2016). This annual precipitation volume is equivalent to an average flow of 1,998 cfs. The annual evaporation of 15 inches is equivalent to an average flow of 949 cfs. The average flow in the Little Deschutes River at La Pine is 179 cfs (equivalent to 2.8 inches). The average groundwater exchange within the basin is therefore estimated to be a net loss of 870 cfs (equivalent to 13.8 inches) to groundwater. The ratio of groundwater loss to surface water outflow in the Little Deschutes River at La Pine is 4.9. This suggests that the ratio of groundwater loss to surface water flow is greater for the Little Deschutes River above La Pine as a whole than it is for just the portion of Crescent Creek above Crescent Dam.

Long-term historical records were obtained and analyzed to compare regulated and unregulated flows in Crescent Creek below Crescent Dam and in the Little Deschutes River at La Pine. Historical records were obtained from the following sources, and used to reconstruct unregulated flows:

- United States Bureau of Reclamation (Reclamation) 2016. Daily storage records for Crescent Lake Reservoir, Calendar Years 1983 through 2015.
- Oregon Water Resources Department (OWRD) 2016a. Daily flows in Crescent Creek below Crescent Dam, Calendar Years 1983 through 2015.
- Oregon Water Resources Department (OWRD) 2016b. Daily flows in the Little Deschutes River at La Pine, Calendar Years 1983 through 2015.

Historical daily records for Calendar Years 1983 through 2015 were obtained for Crescent Lake Reservoir storage, and for daily flows in Crescent Creek below Crescent Dam (Gage No. 14060000) and in the Little Deschutes River at La Pine (Gage No. 14063000). These records were reviewed to identify missing data gaps. The small number of gaps found in this manner were filled with estimates based on a linear assumption. The data were also reviewed to identify any obvious anomalies, and these were adjusted. Data were then analyzed to calculate unregulated flows in Crescent Creek below Crescent Dam and in the Little Deschutes River at La Pine.

In general, the daily change in storage for a reservoir is equal to the total reservoir inflow volume minus the total reservoir outflow volume. The total reservoir inflow is equal to the surface water inflow plus the groundwater inflow plus the inflow from direct precipitation. The total reservoir outflow is equal to the surface water outflow plus the groundwater outflow plus the outflow from evaporation. For Crescent Lake, it was assumed that surface water and groundwater inflow to the reservoir would be the same under regulated and unregulated conditions. The surface area of Crescent Lake Reservoir does not change appreciably over the range of operational water surface elevations. Therefore, it was assumed that daily inflow from direct precipitation and from evaporation losses would be the same under regulated and unregulated flow conditions. In a study performed by the Oregon Water Resources Department (OWRD 2001), it was assumed that seepage losses from Crescent Lake Reservoir are negligible. Based on these assumptions, the average daily surface water flow at Crescent Dam under unregulated conditions is equal to the average daily surface water outflow under regulated conditions plus the daily change in reservoir storage (converted to an average daily flow).

During the initial analyses, it was found there were many days when the calculated average daily outflow under unregulated conditions was negative (an impossible scenario). These occurred when the gage readings indicated a rapid drop in reservoir storage. To adjust the results, it was assumed that the base flow for Crescent Creek below Crescent Dam under unregulated flow conditions is 3 cfs, and the base flow in the Little Deschutes River at La Pine under unregulated conditions is 9 cfs. This constraint was used to adjust the daily storage records in Crescent Lake Reservoir. Historical records indicated it takes about 2 days for changes in release from Crescent Dam to arrive in the Little Deschutes River at La Pine. These assumptions were used to adjust the daily storage records in Crescent Lake Reservoir.

Six gaging stations were installed between September 2013 and January 2015 along Crescent Creek to measure water surface elevation (stage) at hourly intervals. Three of the six stations were established in the creek to support the development of stage/discharge rating curves and hourly flow hydrographs. The other three stations were established in wetlands adjacent to Crescent Creek to derive stage hydrographs that could be used to compare stream discharge with wetland water depth. Barometric pressure was also measured hourly, and used to compensate the stage measurements (subtract barometric pressure from total recorded pressure) at the six gaging stations.

Flows were measured at the three creek gage sites to derive the stage/discharge rating curves. At each site, water depth and velocity were measured at a minimum of 20 points across the wetted width of the creek. The horizontal locations of these points were measured with a survey grade GPS instrument. When water depth at a point was less than 2.5 feet, the velocity was measured at six-tenths of the depth below the water surface. When the depth was greater than 2.5 feet, the velocity was measured at two-tenths and eight-tenths of the depth below the water surface. This process was repeated for three different flows at each site. The rating

curves developed in this way were used to convert stage data to hourly flow hydrographs for each site.

Historical regulated and unregulated daily flows were evaluated for Crescent Creek below Crescent Dam and for the Little Deschutes River at La Pine for the entire 32-year period of 1983 through 2014. Stage/discharge rating curves for these two gages (OWRD 2016a and 2016b) were used to derive historical regulated and unregulated daily stages for the same 32 years. Historical regulated and unregulated daily flows and stages were also examined for 1-year periods representative of wet (1997), average (2007), and dry (1992) years.

Historical data show the full storage capacity of 86,900 acre-feet in Crescent Lake Reservoir is not used in any single year. Annual inflow to the reservoir is considerably less than total storage capacity, and Tumalo Irrigation District (TID), the operator of the reservoir, attempts to release only the average annual inflow in any given year. This results in cyclical patter of reservoir volume as inflow varies from year to year while outflow is held relatively constant.

Daily regulated flow (and stage) in Crescent Creek below Crescent Dam fluctuated within a narrow range, consistent with the large storage capacity of Crescent Lake Reservoir. In contrast, historical flow (and stage) in the Little Deschutes River at La Pine fluctuated over a much wider range due to the substantial unregulated inflow to the basin downstream from Crescent Dam. The unregulated flows in Crescent Creek below Crescent Dam fluctuated over a wider range than the regulated flows. Similarly, unregulated flows at La Pine fluctuated over a wider range than the regulated flows, although the relative difference between regulated and unregulated flows is smaller at La Pine.

Differences between regulated and unregulated hydrographs were apparent in Crescent Creek below Crescent Dam during wet, average and dry years, but regulated and unregulated hydrographs at La Pine were relatively similar for these three years, except during the period of irrigation releases (July – September). Differences between regulated and unregulated hydrographs were apparent in Crescent Creek year-round during wet, average and dry years. Regulated hydrographs for the Little Deschutes River at La Pine were relatively similar to unregulated hydrographs under wet conditions, but the regulated stage hydrograph was noticeably higher than the unregulated hydrograph from mid-June to mid-September during the average year, and from June through mid-August during the dry year.

In Crescent Creek below Marsh Creek, the stage hydrographs indicate that the wetland adjacent to Crescent Creek becomes connected to the creek at higher flows. The water surface elevations at the two wetland gages at Crescent Creek below Highway 58 show very similar patterns, but they have an elevation difference of 0.5 foot or more. This suggests the wetlands are hydraulically linked, but the wetland near the creek is upstream of the wetland away from the creek.

Between Crescent Dam and the confluence with Big Marsh Creek the flows in Crescent Creek increase by 24 to 34 cfs. There is also an increase in Crescent Creek flow from Big Marsh Creek, and a further increase in flow from the wetland near Highway 58 (RM 21.9). Flows then remain the same or decrease from RM 21.9 to RM 1.7 (near the confluence with the Little Deschutes River). Between RM 1.7 on Crescent Creek and the Little Deschutes River at La Pine, flows could either increase or decrease, depending on season.

Interim operations (minimum year-round flow release of 30 cfs) began on February 12, 2015. Regulated water surface elevations in Crescent Creek below Crescent Dam were higher than unregulated elevations from April through mid-November and consistently lower than

unregulated elevations only during January and early February when unregulated flows peaked due to winter storms. During the summer months (July, August, and September), the regulated water surface elevations were over 1 foot higher than the unregulated elevations.

The patterns of regulated and unregulated water surface elevations in Crescent Creek above Marsh Creek are similar to those for Crescent Creek below Crescent Dam. Regulated water surface elevations were higher and more consistent than unregulated elevations in April through mid-November. During the summer months (July, August, and September), the regulated water surface elevations were almost 1 foot higher than the unregulated water surface elevations.

Regulated and unregulated water surface elevations in Crescent Creek below Marsh Creek were similar from November through March, except that unregulated elevations increased for brief periods during rain events. From April through mid-November, regulated water surface elevations were higher than unregulated elevations. In July, August, and September, the regulated water surface elevations were almost 1 foot higher than the unregulated elevations.

As with other locations on Crescent Creek downstream from the confluence with Big Marsh Creek, regulated water surface elevations in Crescent Creek at the confluence with the Little Deschutes River were similar to unregulated elevations in January through March, except for short-term peaks that occurred for unregulated elevations. From April through October, regulated water surface elevations were consistently higher than unregulated elevations. During the summer months (July, August, and September), the regulated water surface elevations were again almost 1 foot higher than the unregulated water surface elevations. As noted previously, data for November and December at RM 1.7 were not collected (the instrument was not downloaded) due to access limitations in early 2016.

The pattern of regulated and unregulated water surface elevations in the Little Deschutes River at La Pine is very similar to that observed for Crescent Creek RM 1.7. Regulated and unregulated water surface elevations showed little difference in January through March, as well as in late November and December. Regulated water surface elevations were about 1.5 feet higher than unregulated elevations during the summer months (July through mid-October).

Trends in regulated and unregulated flow hydrographs in Crescent Creek below Crescent Dam mimic those for water surface elevation previously described. Regulated flows were consistently higher that unregulated flows at all locations from April through mid-November. The differences between regulated and unregulated flows were most pronounced in July through September when water was being released from Crescent Lake for irrigation and regulated flows were about 110 to 140 cfs higher than the unregulated flows. The relative difference between regulated and unregulated flows diminished with increasing distance downstream from Crescent Dam.

From 1983 through 2014, Crescent Lake Reservoir typically stored water from October through June, and then released water from July through September. Under interim operations in 2015, similar seasonal patterns were followed, except that regulated flows during the storage season in 2015 were above the regulated historical median.

It is noteworthy that unregulated flows in 2015 were considerably above the unregulated historical medians in January, February, March and December and below unregulated historical medians in all other months, demonstrating the high degree of natural variation in flows within the Crescent Creek Basin.

From 1983 through 2014, seasonal patterns of median daily stages in Crescent Creek below Crescent Dam are similar to the seasonal patterns of median daily flows. This seasonal pattern was also apparent under interim operations in 2015, except that regulated stages under interim operations were roughly 0.4 foot higher than the historical median during the storage season.

From 1983 through 2014, the seasonal patterns at La Pine were similar to those at Crescent Creek below Crescent Dam, but the differences between regulated and unregulated flows at La Pine were relatively small during the storage season. The most notable difference between regulated and unregulated median daily flows was during the months of July, August and September when irrigation releases from Crescent Lake increased the flow at La Pine by about 110 to 140 cfs and increased the stage by over 1.5 foot. The seasonal patterns under interim operations in 2015 were similar, with the exception that regulated flows were higher than unregulated flows a greater percentage of the year in 2015.

1.0 Introduction

1.1. Background

Eight central Oregon irrigation districts (Arnold, Central Oregon, Lone Pine, North Unit, Ochoco, Swalley, Three Sisters, and Tumalo; collectively the Irrigation Districts) and the City of Prineville, Oregon (City) are seeking Federal Endangered Species Act (ESA) incidental take permits for five species that occur or could occur on lands affected by Iirrigation District and City activities. As required by Section 10 of the ESA, the Irrigation Districts and the City (collectively the Applicants) are preparing the Deschutes Basin Habitat Conservation Plan (DBHCP) to minimize and mitigate the effects of the proposed incidental take on the covered species. The DBHCP is being prepared in cooperation with a multi-stakeholder Working Group representing the U. S. Fish and Wildlife Service (USFWS), National Marine Fisheries Service (NMFS), U. S. Bureau of Reclamation (Reclamation), U. S. Bureau of Land Management (BLM), Oregon Department of Fish and Wildlife (ODFW), Oregon Department of Environmental Quality (ODEQ), Oregon Water Resources Department (OWRD), the Confederated Tribes of the Warm Springs, Crook County, and several non-governmental entities.

One of the five species to be covered by the DBHCP is the Oregon spotted frog (*Rana pretiosa*), which was recently listed under the ESA as threatened. According to the USFWS (2014) the Oregon spotted frog may be affected by irrigation activities such as surface water storage, release, conveyance and diversion. The Oregon spotted frog is known to reside in portions of Crescent Creek and the Little Deschutes River, where it may be influenced by the storage and release of water from Crescent Lake Reservoir. This study provides background information of the hydrological influence of Crescent Lake Reservoir on Crescent Creek and the Little Deschutes River. It will be used, along with other ongoing studies of Oregon spotted frog breeding in these waters, to evaluate potential future reservoir operating regimes for the DBHCP.

Regulation of flows in Crescent Creek began in 1922 when a timber crib dam was built across the outlet of Crescent Lake. The active storage capacity of this reservoir was initially 86,900 acre-feet. Following initial construction, there was a gradual deterioration of timbering and fill. By 1946, the active storage capacity had been reduced to 54,900 acre-feet (32,000 acre-feet less than the original capacity). By 1953, the active storage capacity had been further reduced to 36,000 acre-feet (41% of the original capacity), and the outlet gates had become difficult to operate. A new earthfill dam with a length of 450 feet and a height of 40 feet was constructed at the outlet of Crescent Lake in 1956 to restore the original active storage capacity of 86,900 acre-feet. The outlet works conduit has a capacity of 1,325 cfs, and there is a 45-foot wide uncontrolled spillway in a saddle on the right abutment. The earthfill dam has been well-maintained. As part of the operation and maintenance program, the dam crest was repaired and brought up to grade in 1998.

1.2. Purpose of the Study

The purpose of this study is to quantify the influence of Crescent Lake Reservoir operations on flows in lower Crescent Creek and the Little Deschutes River. The relative contribution of flows in Upper Crescent Creek (above Crescent Dam) to flows in lower Crescent Creek and the Little Deschutes River will be compared on a long-term average basis. Unregulated flows in Crescent Creek and the Little Deschutes River will be compared to regulated flows on a daily basis.

Daily storage records are available from the US Bureau of Reclamation (Reclamation) for Crescent Lake Reservoir for Calendar Years 1983 through 2015 (Reclamation 2016). This study is therefore focused on that 33-year period. Of those 33 years, the first 32 years (1983 through 2014) are considered representative of historical operations. Interim Operations were initiated in 2015 with a minimum year-round release of 30 cfs from Crescent Dam to Crescent Creek. These two periods are considered separately in this study.

2.0 Study Area

Crescent Creek is a tributary to the Little Deschutes River (Figure 2-1). Crescent Lake Reservoir is located high in the Crescent Creek watershed at River Mile (RM) 29, where it captures only headwater runoff. The average outflow from Crescent Lake Reservoir is 54 cubic feet per second (cfs). The largest tributary to Crescent Creek is Big Marsh Creek, which at times can double the flow in Crescent Creek where the two come together. Between Crescent Dam and Big Marsh Creek, Crescent Creek also gains as much as 30 cfs from groundwater discharge (springs). From Big Marsh Creek to the mouth at the Little Deschutes River, Crescent Creek actually loses 1 to 2 cfs back to groundwater (USGS 2004). Approximately 57 miles downstream from its confluence with Crescent Creek, the Little Deschutes River joins the Deschutes River at RM 193. Crescent Dam is the only regulating structure in the Little Deschutes River Basin. The rest of the basin is largely unregulated.

Surface water runoff in the Little Deschutes River Basin is driven by spring snowmelt, with high flows generally occurring in June and low flows at the end of summer. Surface runoff in the Little Deschutes River Basin is also influenced to some extent by interactions with groundwater. In contrast, surface water runoff in the Deschutes River Basin upstream from the confluence with the Little Deschutes River is largely influenced by groundwater. Much of the snowmelt runoff in the Deschutes River Basin is absorbed by porous volcanic rock and it goes directly into the groundwater system, and it interacts with surface water runoff further downstream.

Drainage areas of the Little Deschutes River Basin and sub-basins of the Little Deschutes River Basin are shown in Table 2-1. The average precipitation volume falling in the Crescent Creek sub-basin upstream from Crescent Dam accounts for 13 percent of the average precipitation volume in the Little Deschutes River at La Pine (USGS 2016).

On a long-term average basis, the mean annual precipitation in a basin will be balanced by the sum of surface water outflow, evapotranspiration, and net groundwater exchange. The drainage area of Crescent Creek at the gage below Crescent Dam is 57 square miles and the mean annual precipitation is 60.1 inches (USGS 2016). This annual precipitation volume is equivalent to an average flow of 252 cfs. The mean annual evapotranspiration from the Upper Deschutes Basin is estimated to be 15 inches (USGS 2001), which is equivalent to an average flow of 63 cfs. The average flow in Crescent Creek below Crescent Dam is 48 cfs (equivalent to 11.4 inches). The average groundwater exchange upstream of Crescent Dam is therefore estimated to be a net loss of 141 cfs (equivalent to 33.7 inches) to groundwater. The ratio of groundwater loss to surface water outflow in Crescent Creek at Crescent Dam is 2.9.

The drainage area of the Little Deschutes River at La Pine is 859 square miles and the mean annual precipitation is 31.6 inches (USGS 2016). This annual precipitation volume is equivalent to an average flow of 1,998 cfs. The annual evaporation of 15 inches is equivalent to an average

flow of 949 cfs. The average flow in the Little Deschutes River at La Pine is 179 cfs (equivalent to 2.8 inches). The average groundwater exchange within the basin is therefore estimated to be a net loss of 870 cfs (equivalent to 13.8 inches) to groundwater. The ratio of groundwater loss to surface water outflow in the Little Deschutes River at La Pine is 4.9. This indicates that the ratio of groundwater loss to surface water flow is greater for the Little Deschutes River above La Pine as a whole than it is for just the portion of Crescent Creek above Crescent Dam.

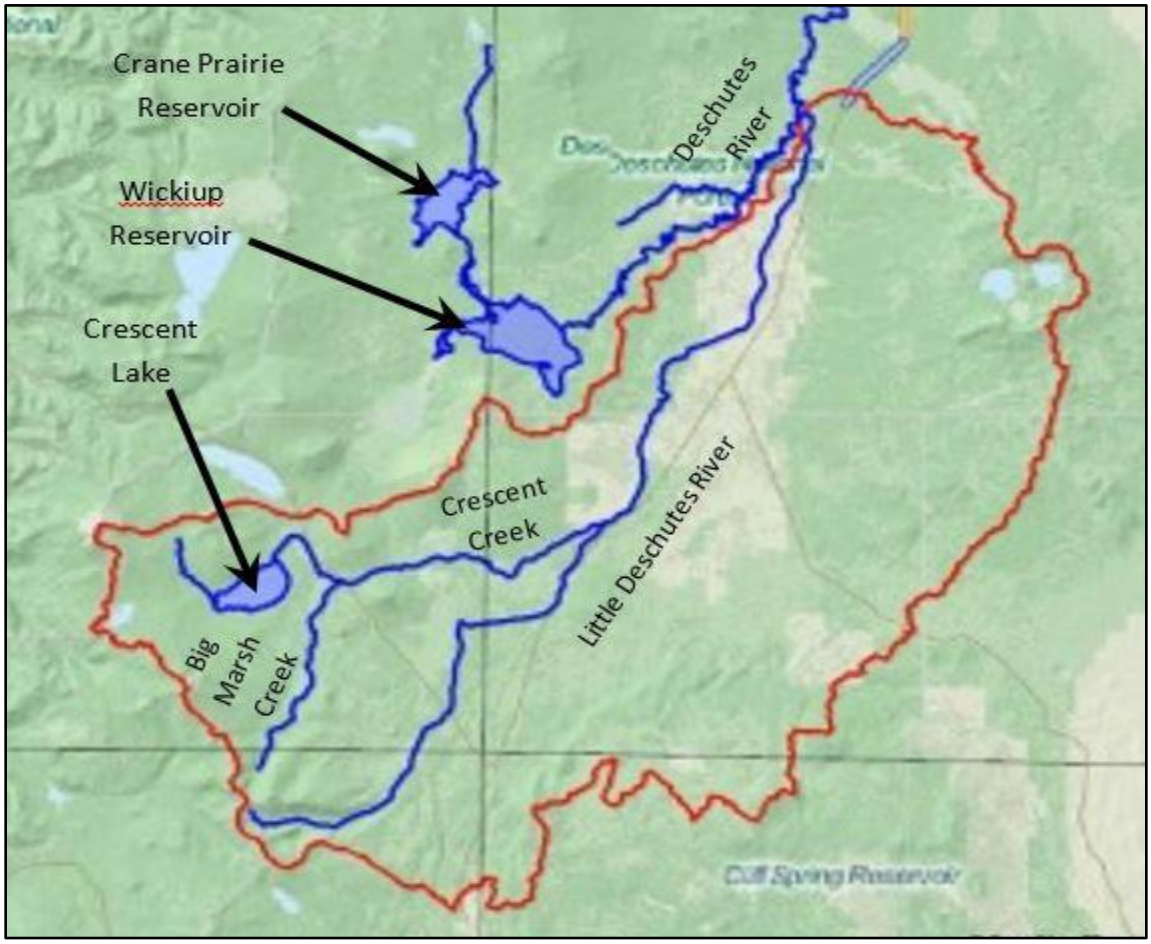

Figure 2-1. Little Deschutes River Basin, Oregon.

Table 2-1 Percentage of average annual precipitation volume in sub-basins of the Little Deschutes River at La Pine, and in Crescent Creek at mouth.

	Little Deschutes River Total	Little Deschutes River at La Pine (OWRD Gage 14063000)	Crescent Creek Total	Crescent Creek Above Crescent Dam	Big Marsh Creek
Drainage Area	1,050 mi^2	859 mi^2	186 mi^2	57 mi^2	49 mi^2
Percent of Average Annual Precipitation Volume in Little Deschutes Basin at La Pine	-	100	31	13	8
Percent of Average Annual Precipitation Volume in Crescent Creek Basin at Mouth	-	-	100	40	26

3.0 Methods

Long-term historical records were obtained and analyzed to compare regulated and unregulated flows in Crescent Creek below Crescent Dam and in the Little Deschutes River at La Pine. Historical records were obtained from the following sources, and used to reconstruct unregulated flows:

- United States Bureau of Reclamation (Reclamation) 2016. Daily storage records for Crescent Lake Reservoir, Calendar Years 1983 through 2015.
- Oregon Water Resources Department (OWRD) 2016a. Daily flows in Crescent Creek below Crescent Dam, Calendar Years 1983 through 2015.
- Oregon Water Resources Department (OWRD) 2016b. Daily flows in the Little Deschutes River at La Pine, Calendar Years 1983 through 2015.

In addition, gaging stations were installed at four locations in Crescent Creek between Crescent Dam and the confluence with the Little Deschutes River to monitor water surface elevation (stage) on an hourly basis. Stream flows were measured at three of the four locations in Crescent Creek, and were used to develop stage/discharge rating curves. These rating curves were used to convert stage hydrographs to flow hydrographs at those locations. These regulated flow hydrographs were then used to estimate flows under unregulated conditions.

3.1. Analysis of Historical Records

Historical daily records for Calendar Years 1983 through 2015 were obtained for Crescent Lake Reservoir storage, and for daily flows in Crescent Creek below Crescent Dam (Gage No. 14060000) and in the Little Deschutes River at La Pine (Gage No. 14063000). Locations of these streamflow gages are shown in Figure 3-1.

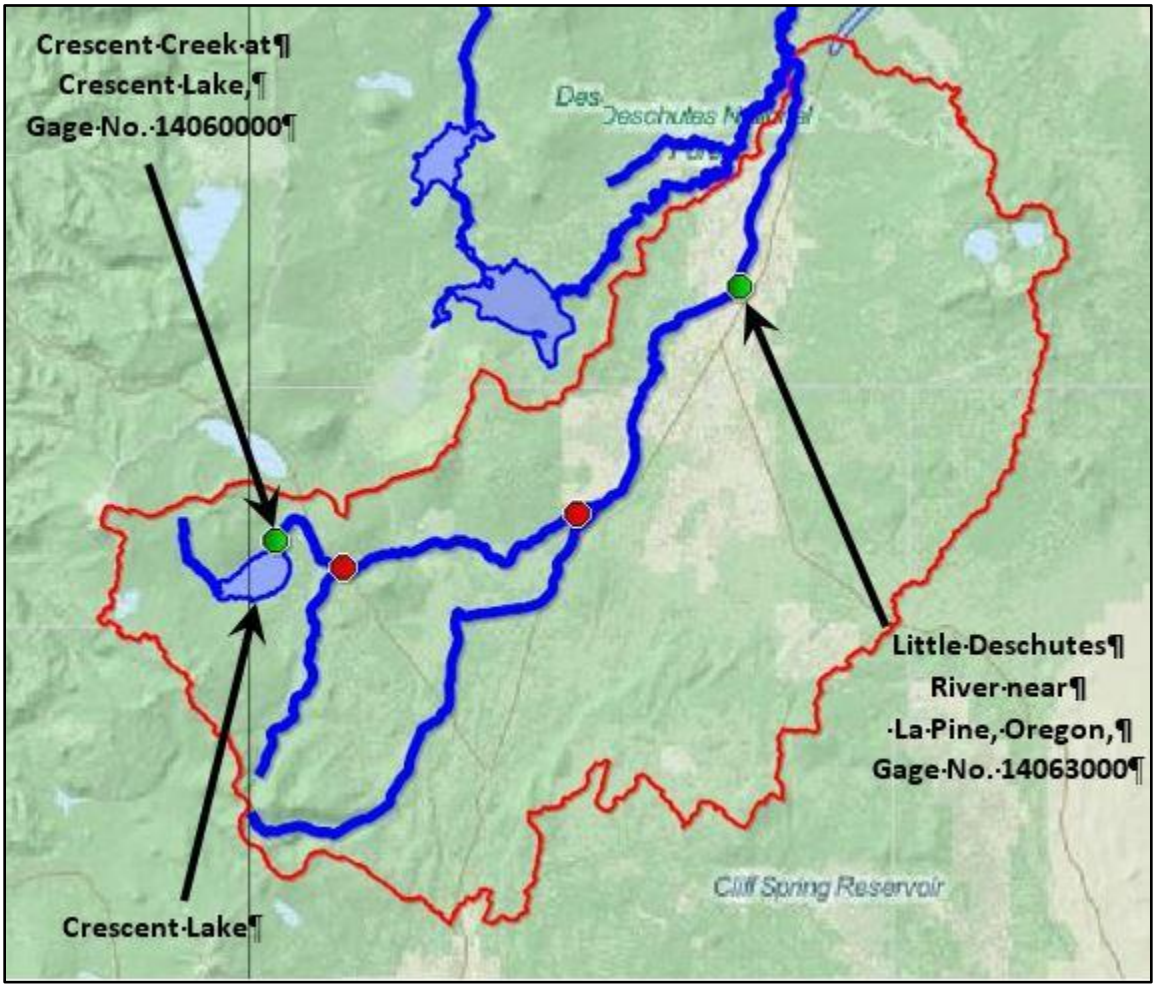

Figure 3-1. Locations of Crescent Lake, Crescent Creek at Crescent Lake (Gage No. 1406000), and Little Deschutes River near La Pine, Oregon (Gage No. 14063000).

These records were reviewed to identify missing data gaps. There were relatively few missing records overall. The missing data gaps were filled with estimates based on a linear assumption. The data were also reviewed to identify any obvious anomalies, and these were adjusted. Data were then analyzed to calculate unregulated flows in Crescent Creek below Crescent Dam and in the Little Deschutes River at La Pine.

The daily change in reservoir storage is equal to the total reservoir inflow volume minus the total reservoir outflow volume (Equation 3-1).

Equation 3-1: $$\Delta S = (Q_{TOTALIN} - Q_{TOTALOUT}) * \left(\frac{1\ acre}{43{,}560\ ft^2}\right) * \left(\frac{24 * 3{,}600\ seconds}{1\ day}\right)$$

Where

ΔS = daily change in reservoir storage in (acre-feet)/day
$Q_{TOTALIN}$ = average daily total reservoir inflow (cfs)
$Q_{TOTALOUT}$ = average daily total reservoir outflow (cfs)

The total reservoir inflow is equal to the surface water inflow plus the groundwater inflow plus the inflow from direct precipitation (Equation 3-2).

Equation 3-2: $$Q_{TOTALIN} = Q_{SWIN} + Q_{GWIN} + Q_{PRECIN}$$

Where
Q_{SWIN} = average daily surface water inflow (cfs)
Q_{GWIN} = average daily groundwater inflow (cfs)
Q_{PRECIN} = average daily inflow from direct precipitation (cfs)

The total reservoir outflow is equal to the surface water outflow plus the groundwater outflow plus the outflow from evaporation (Equation 3-3).

Equation 3-3: $$Q_{TOTALOUT} = Q_{SWOUT} + Q_{GWOUT} + Q_{EVAPOUT}$$

Where
Q_{SWOUT} = average daily surface water outflow (cfs)
Q_{GWOUT} = average daily groundwater outflow (cfs)
$Q_{EVAPOUT}$ = average daily outflow from evaporation (cfs)

In these analyses, it was assumed that surface water and groundwater inflow to Crescent Lake Reservoir would be the same under regulated and unregulated conditions. The surface area of Crescent Lake Reservoir does not change appreciably over the range of operational water surface elevations. Therefore, it was assumed that daily inflow from direct precipitation and from evaporation losses would be the same under regulated and unregulated flow conditions. In a study performed by the Oregon Water Resources Department (OWRD 2001), it was assumed that seepage losses from Crescent Lake Reservoir are negligible. Based on these assumptions, the following equation was used to estimate unregulated flows in Crescent Creek below Crescent Dam:

Equation 3-4: $$Q_{UNREG} = Q_{REG} + \Delta S * \left(\frac{43{,}560\ ft^2}{1\ acre}\right) * \left(\frac{1\ day}{24*3{,}600\ seconds}\right)$$

Where
Q_{UNREG} = average daily surface water outflow under unregulated conditions (cfs)
Q_{REG} = average daily surface water outflow under regulated conditions (cfs)

When Equation 3-4 was initially applied, it was found there were many days when Q_{UNREG} was negative. These occurred when the gage readings indicated a rapid drop in reservoir storage. To adjust the results, it was assumed that the base flow for Crescent Creek below Crescent Dam under unregulated flow conditions is 3 cfs. The following equation was used to adjust the storage records and prevent Q_{UNREG} from dropping below 3 cfs:

Equation 3-5: $$\Delta S > (3\ cfs - Q_{REG}) * \left(\frac{1\ acre}{43{,}560\ ft^2}\right) * \left(\frac{24*3{,}600\ seconds}{1\ day}\right)$$

A similar adjustment was also used for storage based on the flows measured in the Little Deschutes River at La Pine. Historical records indicated it takes about 2 days for changes in release from Crescent Dam to arrive in the Little Deschutes River at La Pine. The base flow in the Little Deschutes River at La Pine was assumed to be 9 cfs. The following equation was used

to adjust the change in storage in Crescent Lake Reservoir to prevent the unregulated flow in the Little Deschutes River at La Pine from dropping below 9 cfs:

Equation 3-6: $$\Delta S > (9\ cfs - Q_{REG}) * \left(\frac{1\ acre}{43{,}560\ ft^2}\right) * \left(\frac{24 * 3{,}600\ seconds}{1\ day}\right)$$

Final adjustments to the change in storage were based on the maximum of the adjustments from Equations 3-5 and 3-6.

3.2. New Gaging Stations on Crescent Creek

Six gaging stations were installed between September 2013 and January 2015 along Crescent Creek to measure water surface elevation (stage) at hourly intervals. Three of the six stations were established in the Creek at the locations shown in Figure 3-2 to support the development of stage/discharge rating curves and hourly flow hydrographs. The other three stations were established in wetlands adjacent to Crescent Creek at the locations shown in Figure 3-3 to derive stage hydrographs. Barometric pressure was also measured hourly at the locations shown in Figure 3-4, and used to compensate the stage measurements (subtract barometric pressure from total recorded pressure) at the six gaging stations.

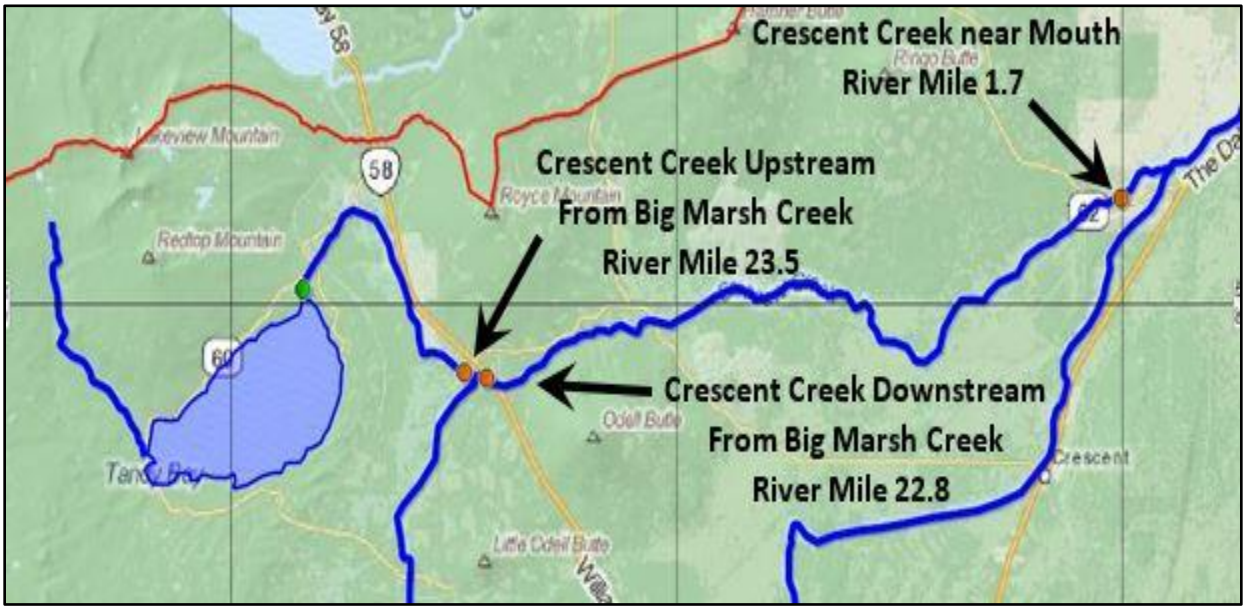

Figure 3-2. Locations of pressure transducers installed to measure both stage and flow on Crescent Creek.

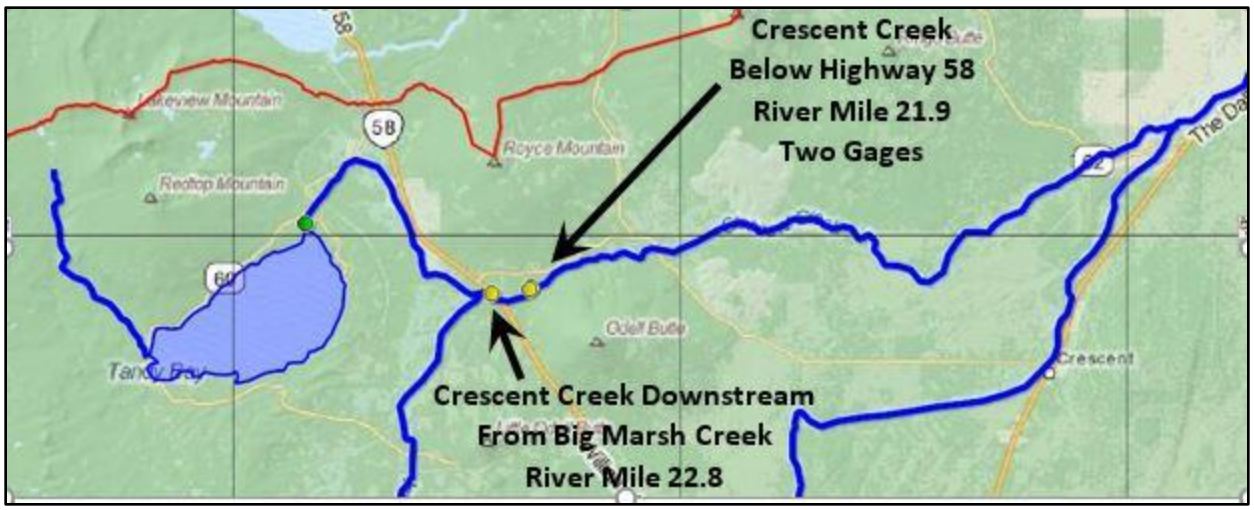

Figure 3-3. Locations of pressure transducers installed to measure stage only in wetlands associated with Crescent Creek.

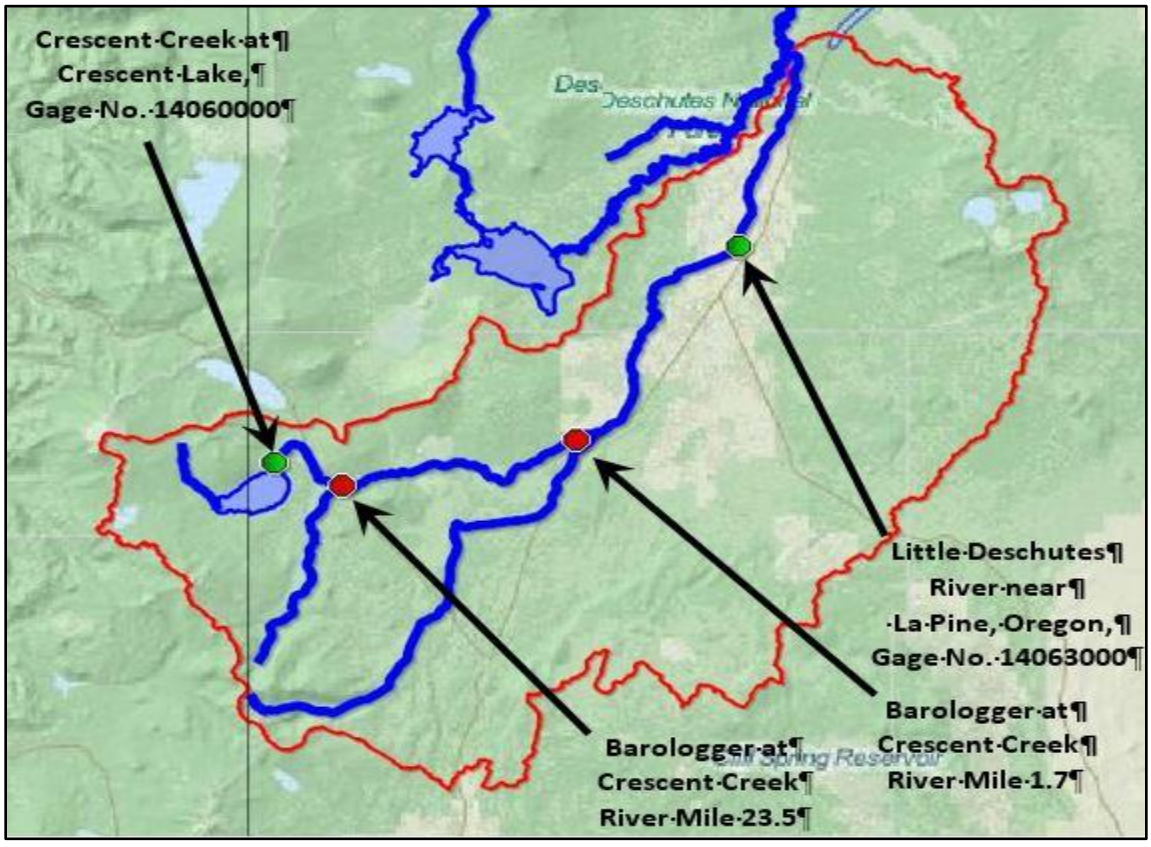

Figure 3-4. Locations of Barologgers installed to monitor barometric pressure along Crescent Creek.

3.2.1. Field Methods

Stage was measured using Solinst Leveloggers, launched to measure water pressure at hourly intervals. These were housed in perforated steel or PVC well points driven into the stream bed or wetland until bedrock or compacted soil was encountered. Extension pipes were added when combined soil and water depth exceeded the length of the well point (36 inches). The pressure transducers were suspended from the tops of the pipes. The top elevation and location (latitude and longitude) of each pipe was determined using a survey-grade GPS instrument. Water surface elevation was surveyed relative to the top of the pipe when the gaging station was initially established, and again during subsequent field visits to allow for correction of instrument drift as per manufacturer's recommendations.

Barometric pressure was measured hourly using Solinst Barologgers. These were suspended above expected water surface elevations, either within Levelogger pipes or in nearby uplands.

Flows were measured at the three locations shown in Figure 3-2. Depth and velocity were measured on at least 20 locations across the wetted width of the creek. The horizontal locations of these measurements were measured with a survey grade GPS instrument. When the depth was less than 2.5 feet, the velocity was measured at six-tenths of the depth below the water surface. When the depth was greater than 2.5 feet, the velocity was measured at two-tenths and eight-tenths of the depth below the water surface. Flows were measured on three different occasions at each of the three locations.

3.2.2. Analytical Methods

The raw pressure measurements from each Levelogger were adjusted using the barometric pressure measurements from the nearest Barologger. Drift corrections were also applied to the stage measurements. These calculations were performed to derive stage hydrographs at each of the six gaging stations.

The flows measured at each site were combined with concurrent water surface elevation measurements to develop a stage-discharge rating curve for each location. These stage/discharge rating curves were used to derive flow hydrographs at the locations shown in Figure 3-2.

4.0 Results

Results were derived for two different time periods. Results from Calendar Year 1983 through 2014 are representative of long-term historical operations. Results from Calendar Year 2015 reflect Interim Operations with a year-round minimum release of 30 cfs from Crescent Lake to Crescent Creek.

4.1. Historical Records

Historical regulated and unregulated daily flows were derived from Calendar Year 1983 through 2014 for Crescent Creek below Crescent Dam and for the Little Deschutes River at La Pine. Stage/discharge rating curves for these two gages were used to derive historical regulated and unregulated daily stages for Crescent Creek below Crescent Dam and for the Little Deschutes

River at La Pine. Historical records of regulated and unregulated daily flows and stages were also examined for a wet year (1997), and average year (2007), and a dry year (1992).

4.1.1. Historical Regulated and Unregulated Flows

Historical daily storage records from Crescent Lake Reservoir are shown in Figure 4-1. The full storage capacity of 86,900 acre-feet is not used in any single year. It takes multiple years to cycle up and down through the full range of active storage.

Historical daily flow records from Crescent Creek below Crescent Dam are also shown in Figure 4-1. Daily flows in Crescent Creek fluctuated within a narrow range, consistent with the large storage capacity of Crescent Lake Reservoir.

Historical daily flow records from the Little Deschutes River at La Pine (Figure 4-1) reflect substantial unregulated inflow to the basin downstream from Crescent Dam. Flows fluctuated over a much wider seasonal range in the Little Deschutes River at La Pine than they did in Crescent Creek below Crescent Dam.

Reported and adjusted daily storage records are shown in Figure 4-2. Relatively minor adjustments to storage records were needed to prevent negative flows in Crescent Creek below Crescent Dam and in the Little Deschutes River at La Pine.

Historical regulated and unregulated flows in Crescent Creek below Crescent Dam are compared in Figure 4-2. The unregulated flows fluctuate over a wider range than the regulated flows.

Historical regulated and unregulated flows in the Little Deschutes River at La Pine are also compared in Figure 4-2. Similar to Crescent Creek below Crescent Dam, unregulated flows at La Pine fluctuate over a wider range than the regulated flows, although the relative difference between regulated and un regulated flows is smaller at La Pine.

Reported and adjusted daily storage records in Crescent Lake Reservoir are shown in Figures 4-3, 4-4, and 4-5 for a wet, average and dry year, respectively. Relatively minor adjustments to storage records were needed to prevent negative flows in Crescent Creek below Crescent Dam and in the Little Deschutes River at La Pine during these three years.

Regulated and unregulated daily flows in Crescent Creek and the Little Deschutes River for wet, average, and dry years are also shown in Figures 4-3, 4-4, and 4-5, respectively. Differences between regulated and unregulated hydrographs were apparent in Crescent Creek during wet, average and dry years, but regulated and unregulated hydrographs at La Pine were relatively similar for these three years, except during the period of irrigation releases (July – September).

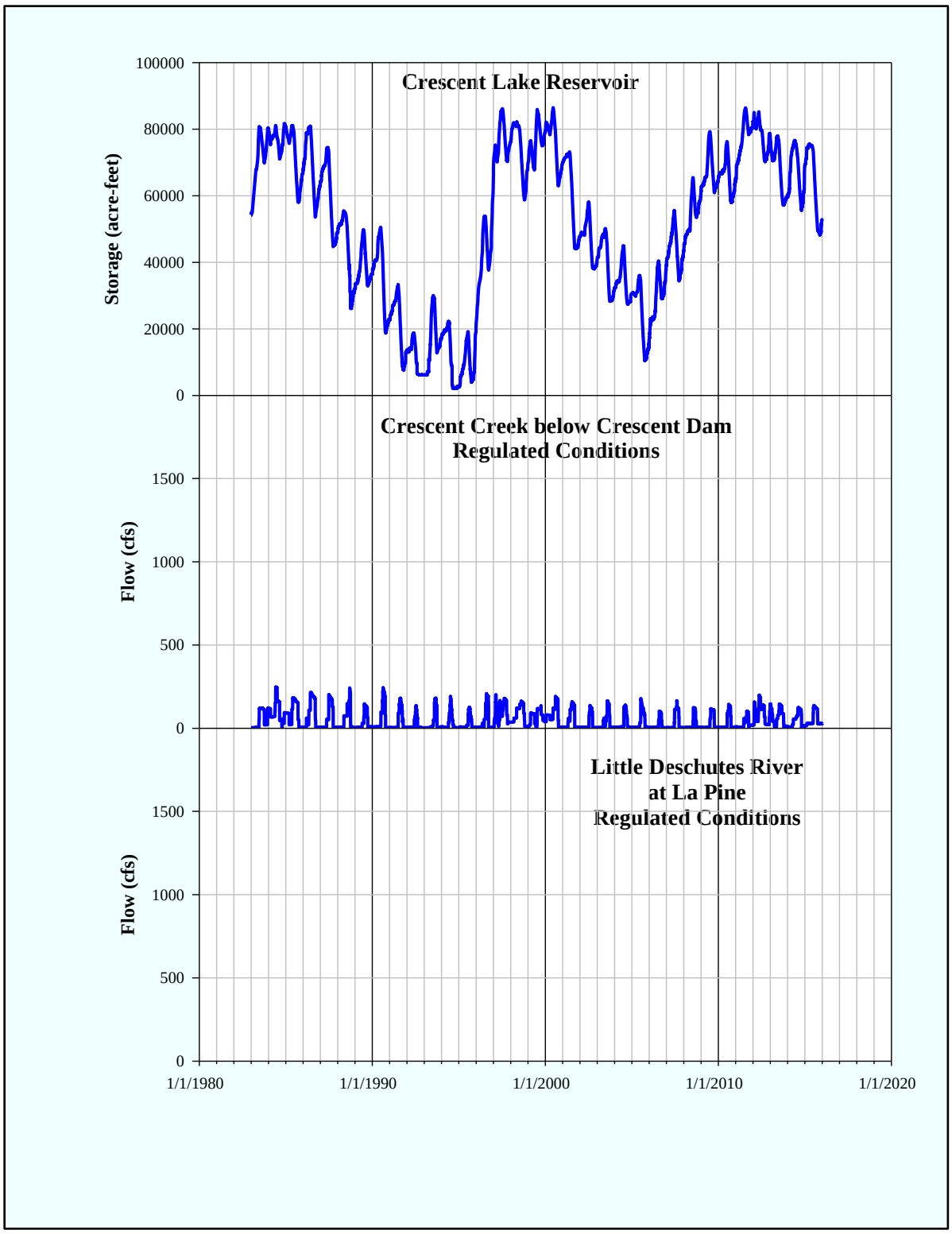

Figure 4-1. **Historical daily storage records from Crescent Lake Reservoir, daily flow records from Crescent Creek below Crescent Dam, and daily flow records from the Little Deschutes River at La Pine, Calendar Years 1983 through 2015.**

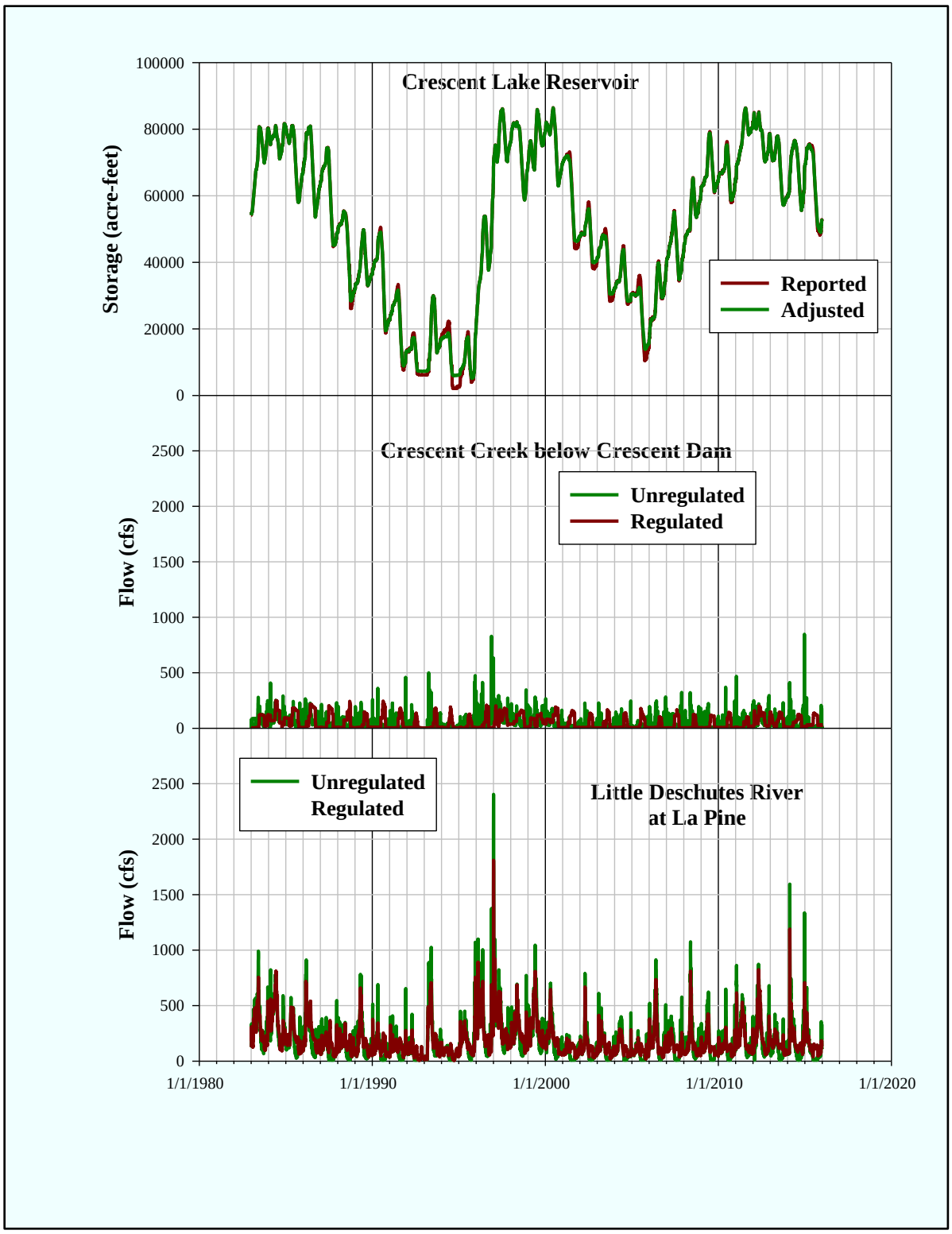

Figure 4-2. **Reported and adjusted daily storage records from Crescent Lake Reservoir, unregulated and regulated daily flows in Crescent Creek below Crescent Dam, and unregulated and regulated daily flows in the Little Deschutes River at La Pine, Calendar Years 1983 through 2015.**

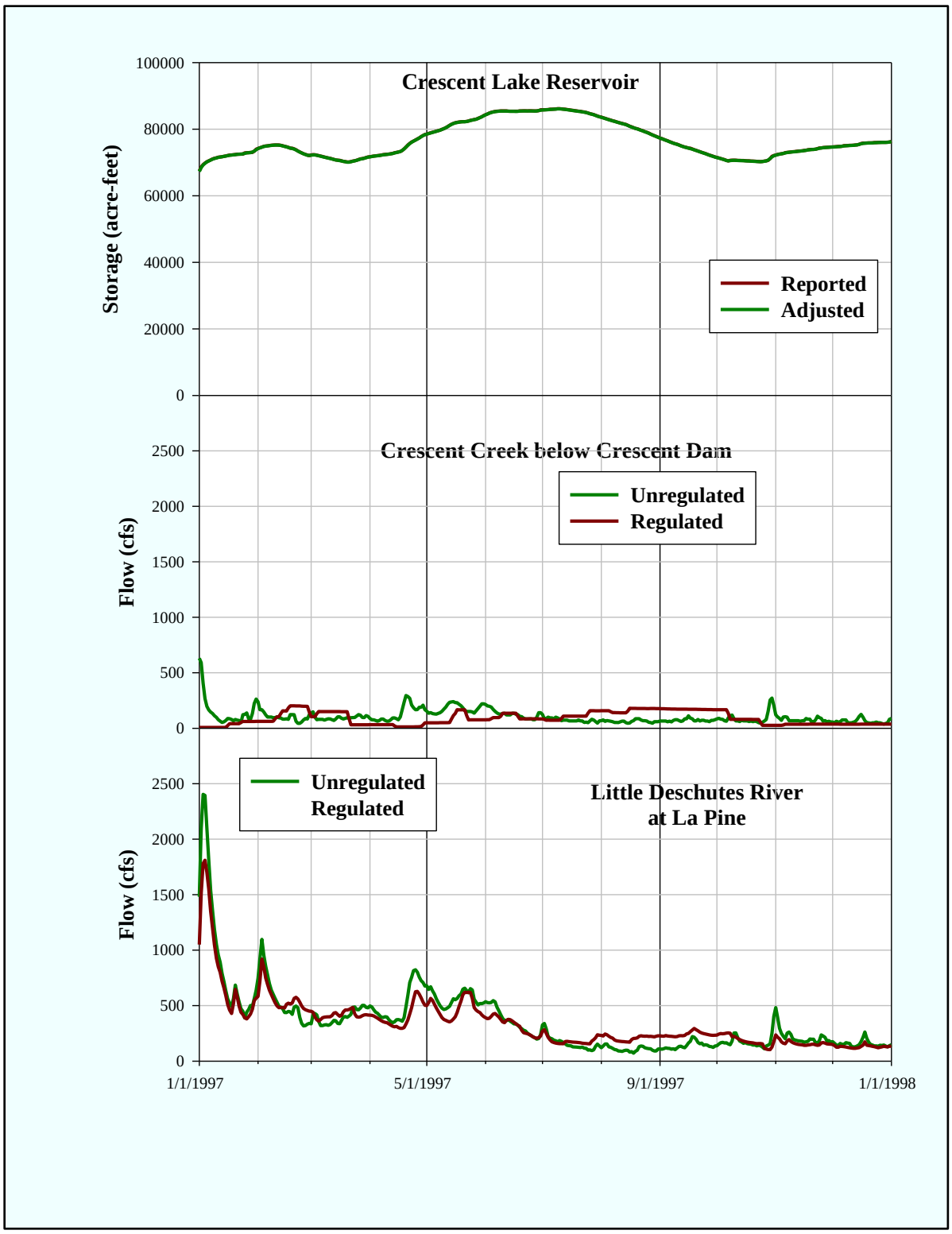

Figure 4-3. **Reported and adjusted daily storage records from Crescent Lake Reservoir, unregulated and regulated daily flows in Crescent Creek below Crescent Dam, and unregulated and regulated daily flows in the Little Deschutes River at La Pine, Calendar Year 1997 (wet year).**

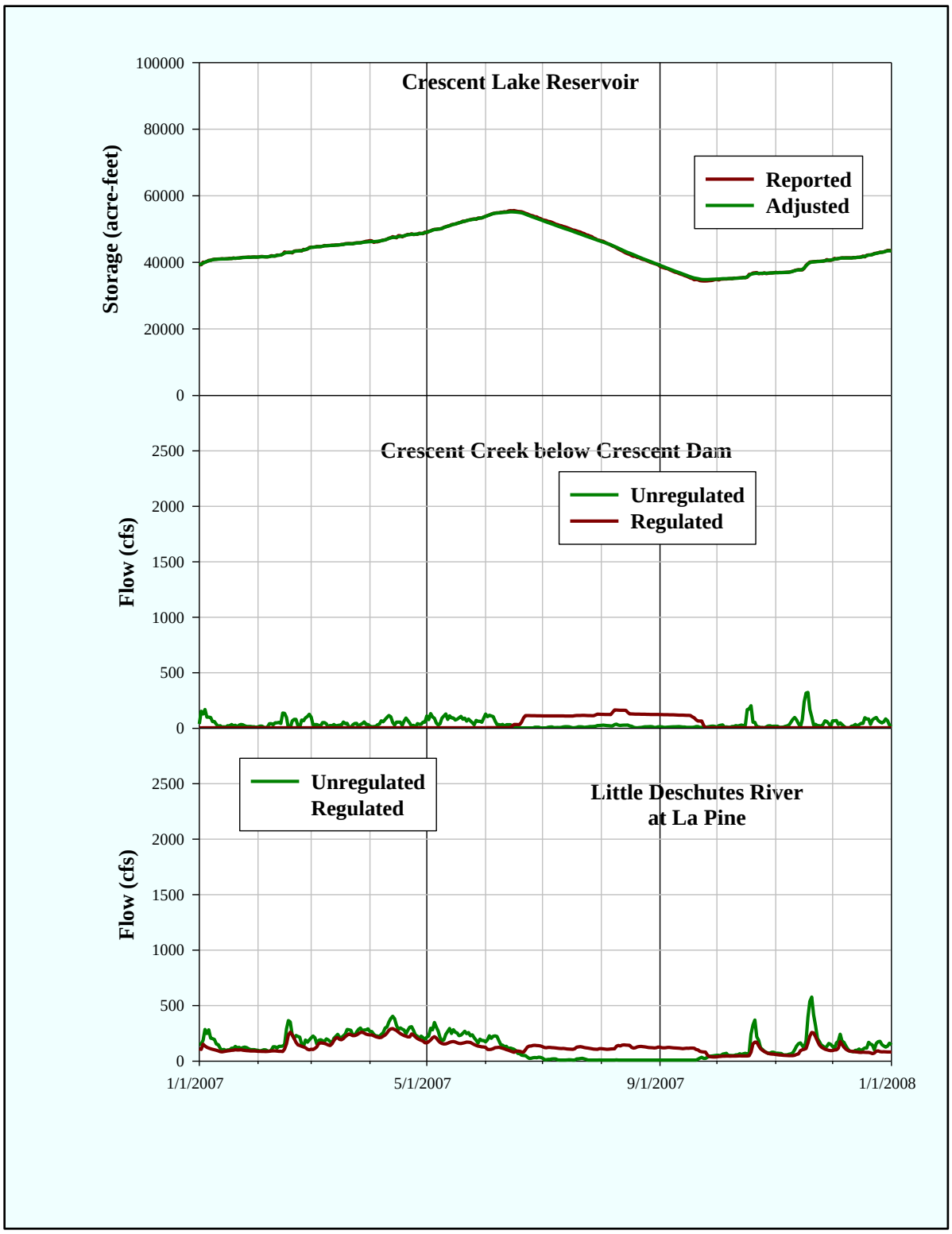

Figure 4-4. **Reported and adjusted daily storage records from Crescent Lake Reservoir, unregulated and regulated daily flows in Crescent Creek below Crescent Dam, and unregulated and regulated daily flows in the Little Deschutes River at La Pine, Calendar Year 2007 (average year).**

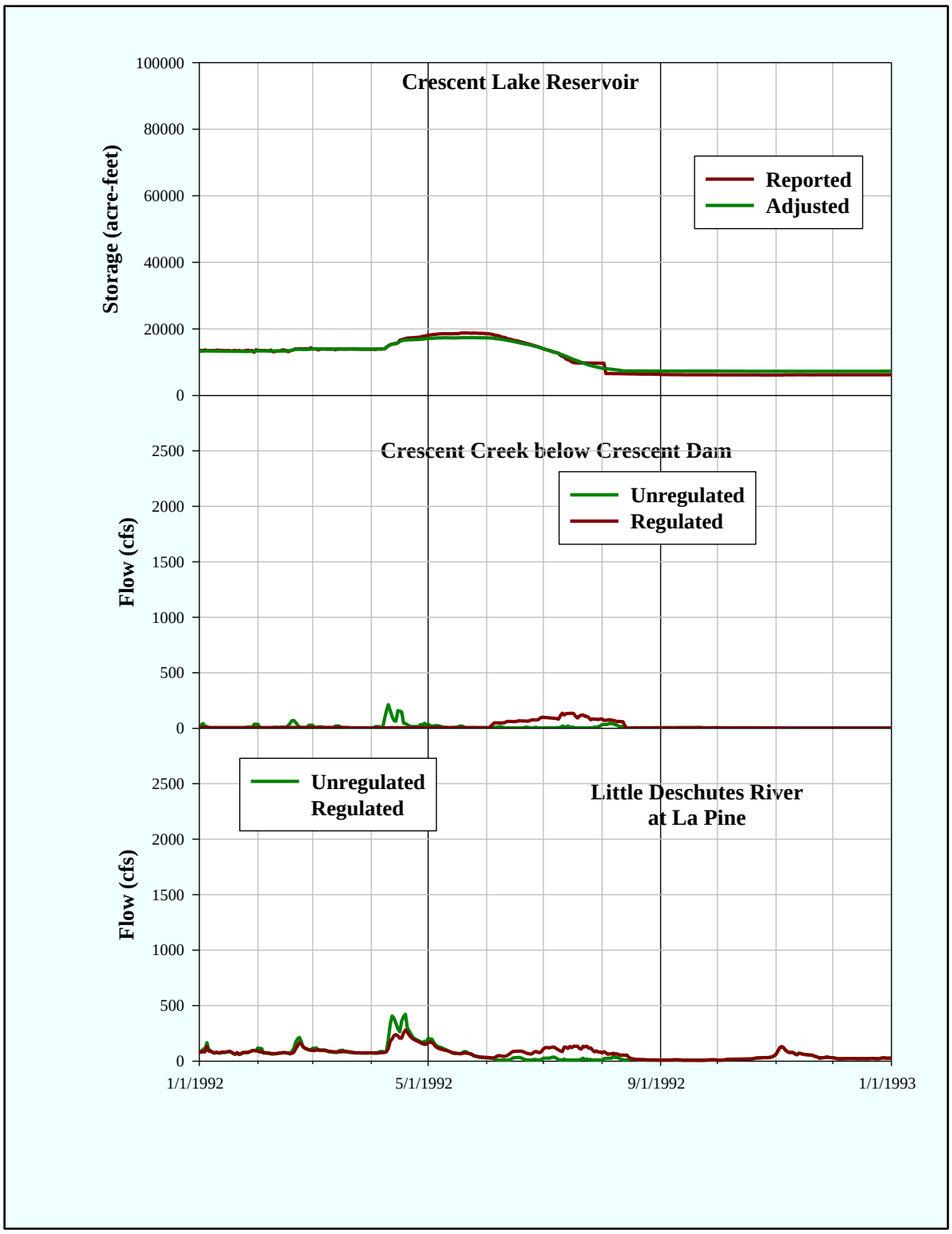

Figure 4-5. **Reported and adjusted daily storage records from Crescent Lake Reservoir, unregulated and regulated daily flows in Crescent Creek below Crescent dam, and unregulated and regulated daily flows in the Little Deschutes River at La Pine, Calendar Year 1992 (dry year).**

4.1.2. Stage/Discharge Rating Curves

Stage/discharge rating curves for Crescent Creek below Crescent Dam and for the Little Deschutes River at La Pine are shown in Figures 4-6 and 4-7, respectively. The relationship between stage and discharge is relatively constant for Crescent Creek between 50 and 300 cfs. The relationship on the Little Deschutes River at La Pine is also relatively constant up to about 500 cfs.

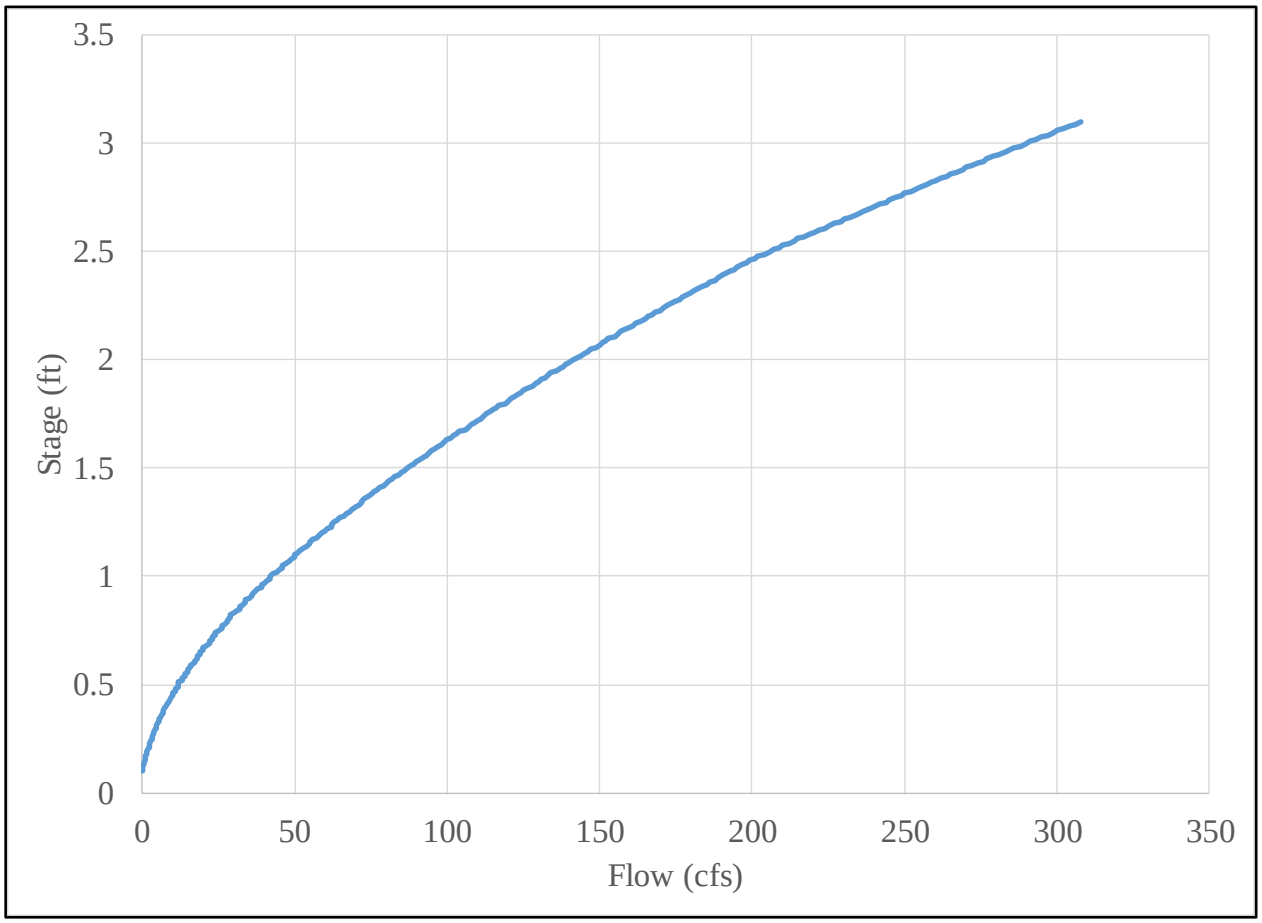

Figure 4-6. Stage/discharge rating curve for Crescent Creek below Crescent Dam.

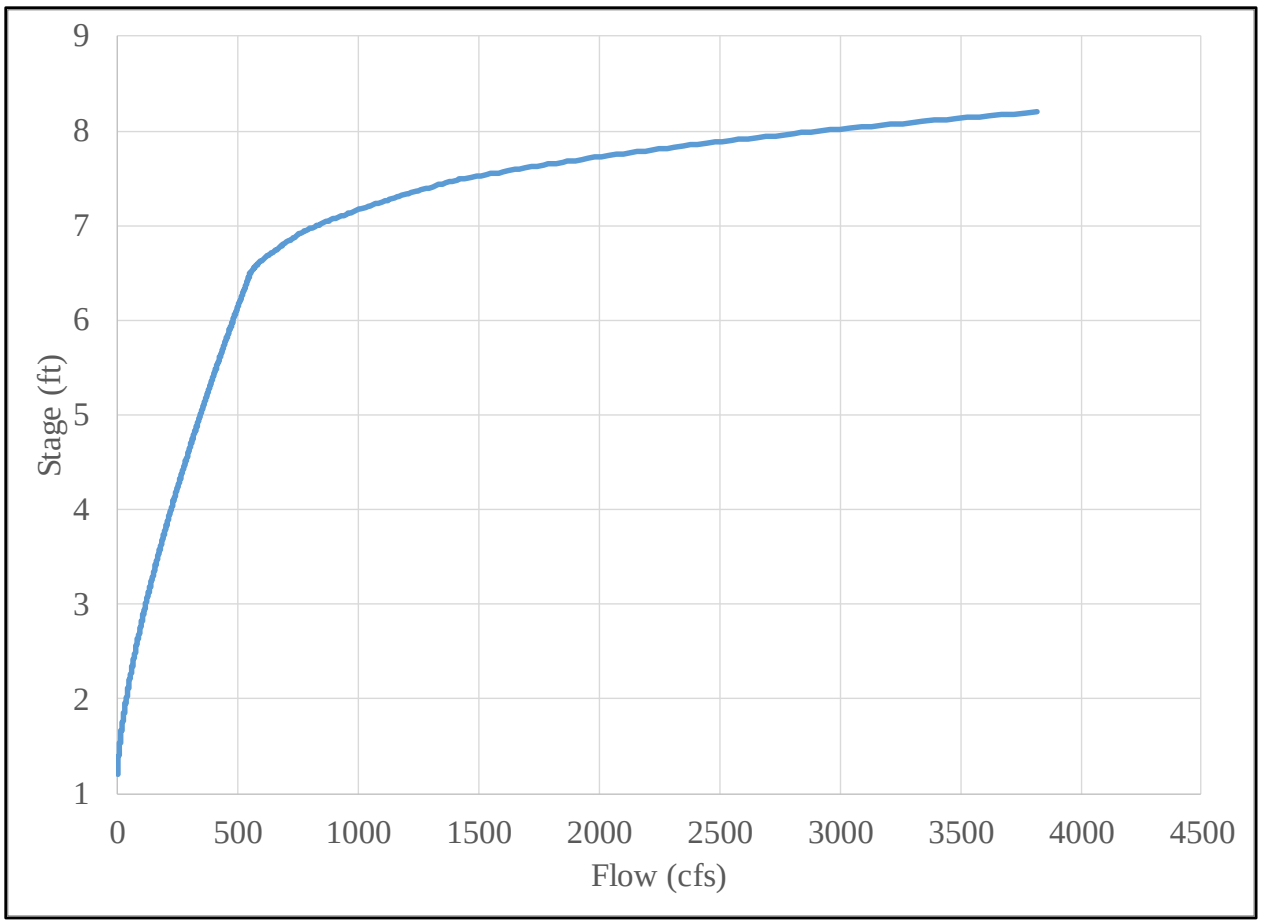

Figure 4-7. Stage/discharge rating curve for the Little Deschutes River at La Pine.

4.1.3. Historical Regulated and Unregulated Stages

The rating curves described in Section 4.1.2 were used to derive stage hydrographs from the flow hydrographs described in Section 4.1.1. These stage hydrographs are presented in this section. Historical regulated and unregulated stages are compared for Crescent Creek below Crescent Dam and the Little Deschutes River at La Pine in Figure 4-8. The unregulated stages fluctuate over a wider range than the regulated flows at both locations, but the relative differences between regulated and unregulated stages are smaller for the Little Deschutes River at La Pine.

Regulated and unregulated daily stages in Crescent Creek and the Little Deschutes River are shown for wet, average, and dry years in Figures 4-9, 4-10, and 4-11, respectively. Differences between regulated and unregulated hydrographs were apparent in Crescent Creek year-round during wet, average and dry years. Regulated hydrographs for the Little Deschutes River at La Pine were relatively similar to unregulated hydrographs under wet conditions, but the regulated stage hydrograph was noticeably higher than the unregulated hydrograph from mid-June to mid-September during the average year (Figure 4-10), and from June through mid-August during the dry year.

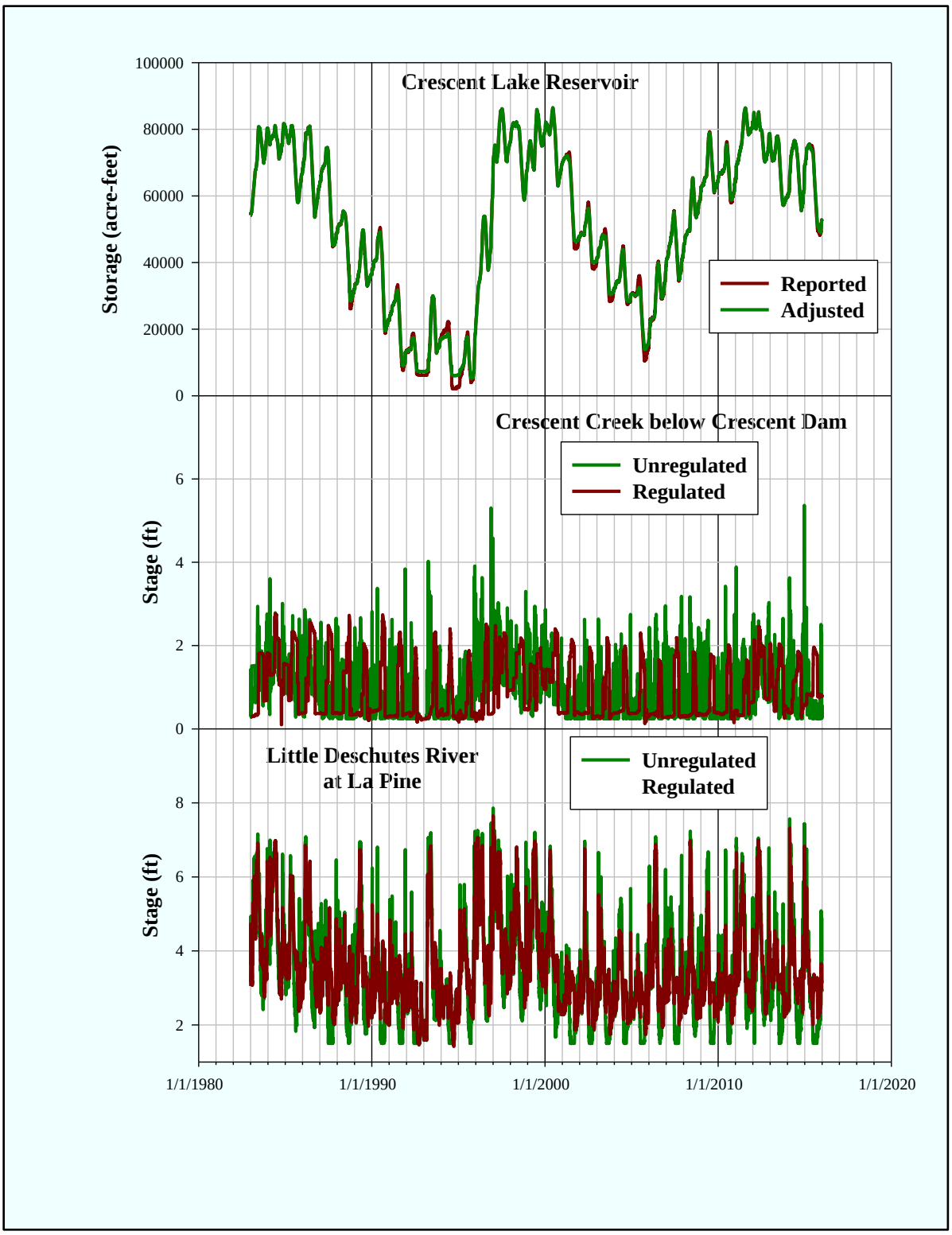

Figure 4-8. **Reported and adjusted daily storage records from Crescent Lake Reservoir, unregulated and regulated daily stages in Crescent Creek below Crescent Dam, and unregulated and regulated daily stages in the Little Deschutes River at La Pine, Calendar Years 1983 through 2015.**

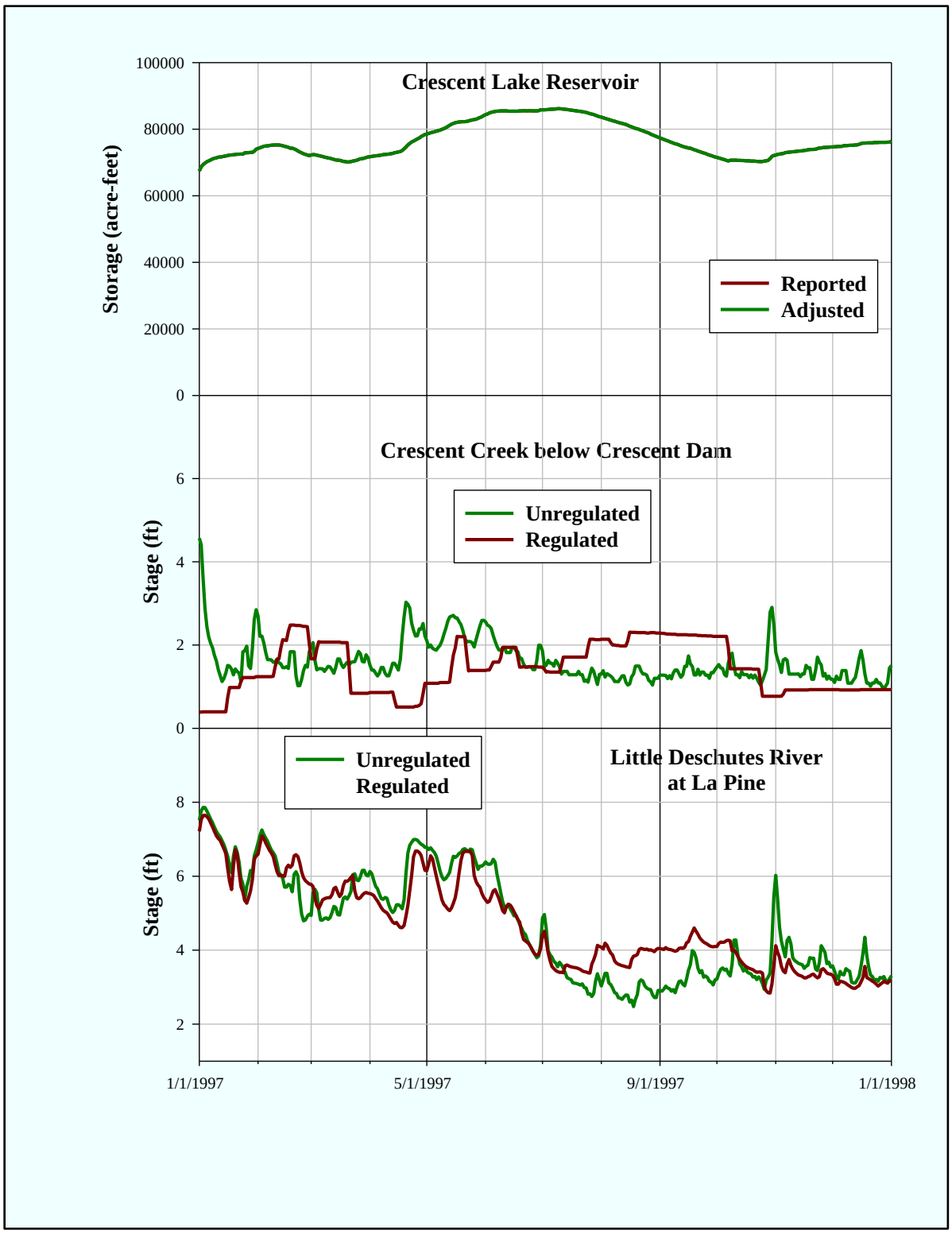

Figure 4-9. **Reported and adjusted daily storage records from Crescent Lake Reservoir, unregulated and regulated daily stages in Crescent Creek below Crescent Dam, and unregulated and regulated daily stages in the Little Deschutes River at La Pine, Calendar Year 1997 (wet year).**

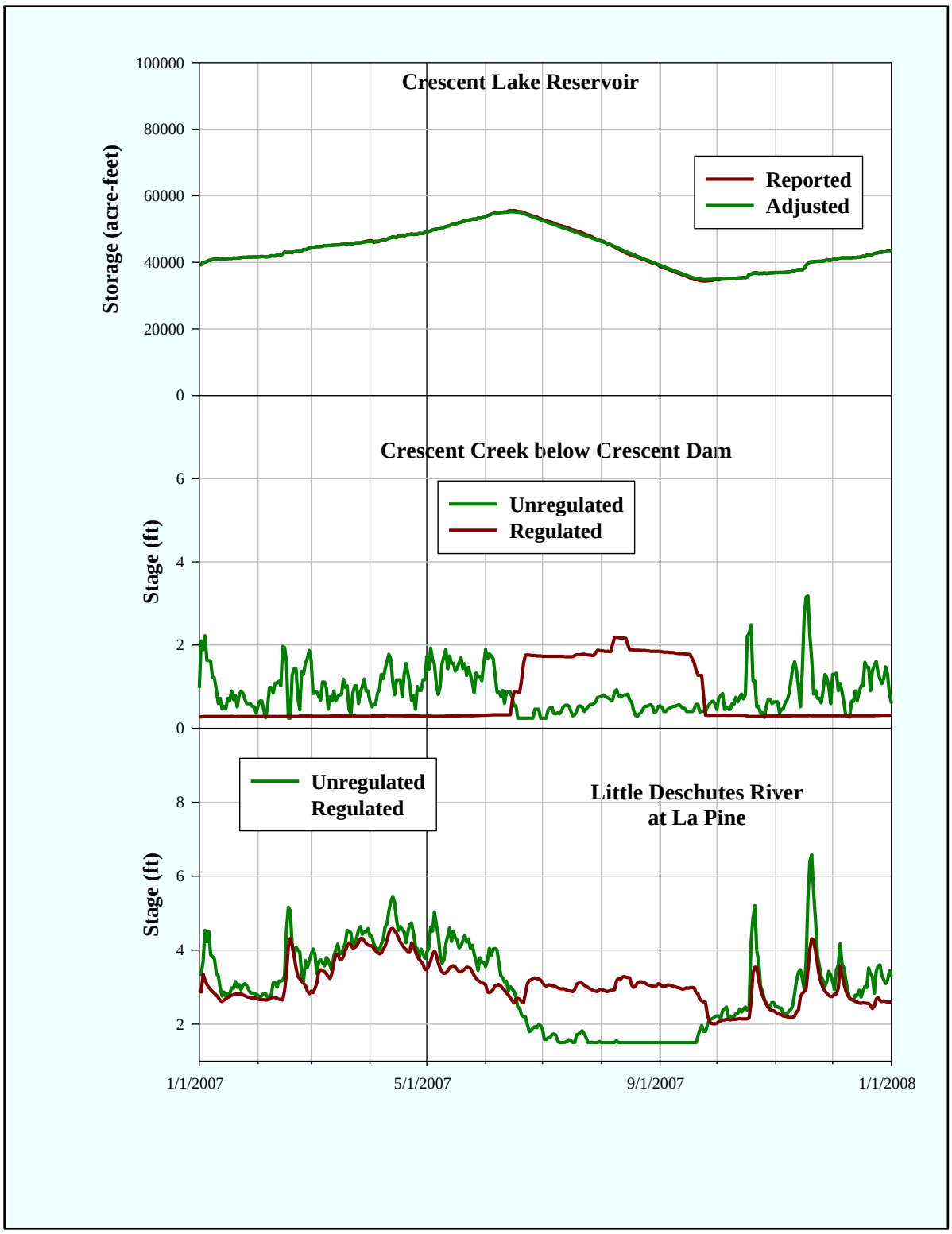

Figure 4-10. Reported and adjusted daily storage records from Crescent Lake Reservoir, unregulated and regulated daily stages in Crescent Creek below Crescent Dam, and unregulated and regulated daily stages in the Little Deschutes River at La Pine, Calendar Year 2007 (average year).

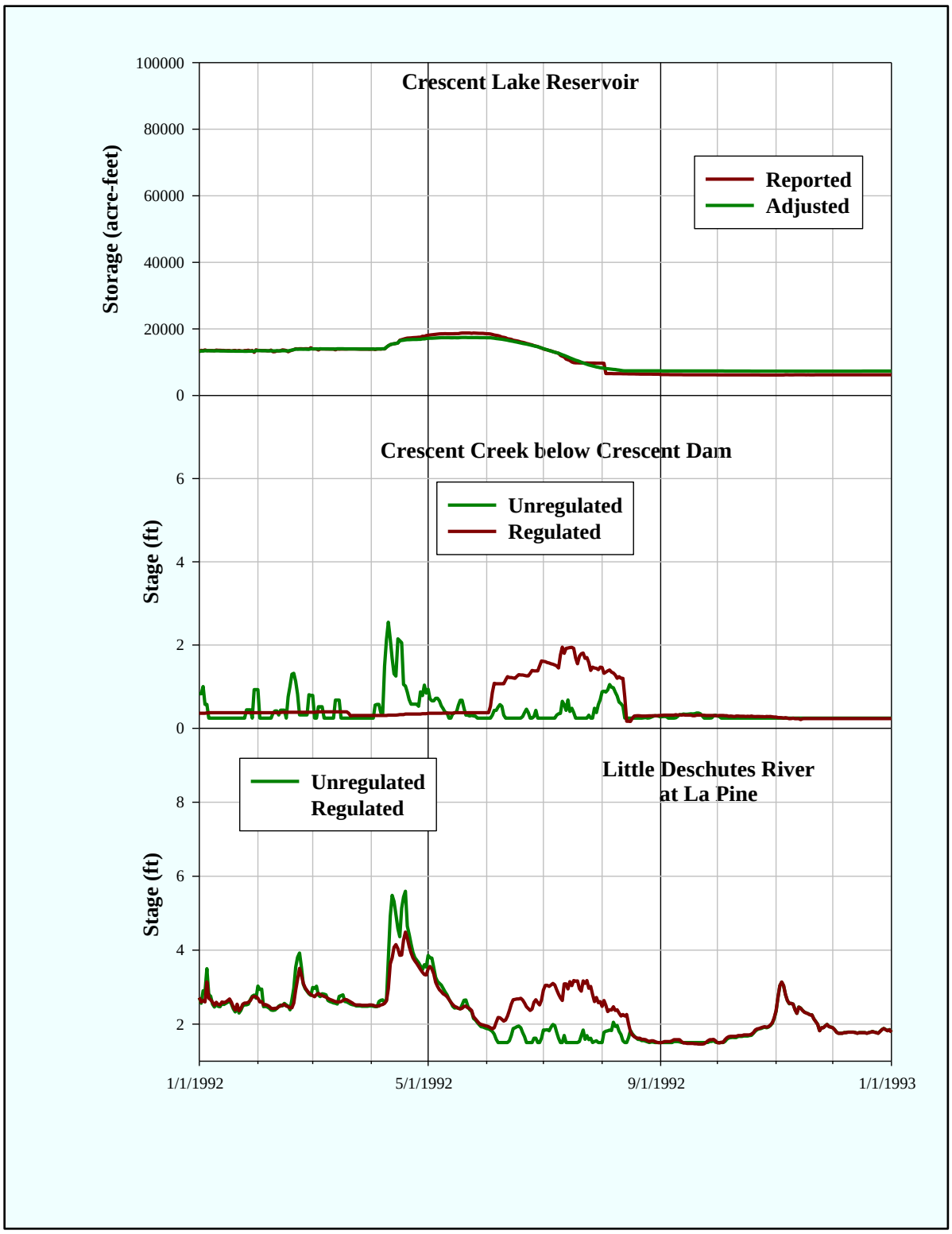

Figure 4-11. Reported and adjusted daily storage records from Crescent Lake Reservoir, unregulated and regulated daily stages in Crescent Creek below Crescent Dam, and unregulated and regulated daily stages in the Little Deschutes River at La Pine, Calendar Year 1992 (dry year).

4.2. New Gages on Crescent Creek

The location (latitude and longitude) and elevation at top of pipe were determined for each of the new gages along Crescent Creek with survey-grade GPS (Table 4-1). Water surface elevations were surveyed when each of the gages were initially installed. Elevations were surveyed by measuring the vertical distance from the water surface to the top of pipe with a tape measure. The data and time when measurements were initiated and the initial water surface elevation for each gage are listed in Table 4-2.

Table 4-1. Locations of gaging stations installed on Crescent Creek.

Data Recorded	Crescent Creek River Mile	Location Name	Latitude (N)	Longitude (W)	Elevation at Top of Pipe (ft, NAVD 88)
Stage and Flow	1.7	BLM Wetland	43° 31’ 22.196”	121° 40’ 00.755”	4,338.30
	22.8	Below Big Marsh Creek	43° 29’ 01.056”	121° 54’ 15.439”	4,630.25
	23.5	Above Big Marsh Creek	43° 29’ 05.529”	121° 54’ 45.309”	4,640.82
Stage	21.9	Below Highway 58; in Wetland Near Creek	43° 29’ 06.189”	121° 53’ 21.472”	4,612.81
	21.9	Below Highway 58; in Wetland away from Creek	43° 29’ 08.276”	121° 53’ 20.398”	4,611.83
	22.8	Wetland Below Big Marsh Creek	43° 29’ 02.532”	121° 54’ 12.744”	4,629.45
Barometric Pressure	1.7	BLM Wetland	43° 31’ 22.196”	121° 40’ 00.755”	N/A
	22.8	Below Big Marsh Creek	43° 29’ 01.05”	121° 54’ 15.43”	N/A

Table 4-2. Dates and times measurements were initiated and initial water surface elevations at gaging stations on Crescent Creek.

Data Recorded	Crescent Creek River Mile	Location Name	Date/Time of Initial Measurements	Initial Water Surface Elevation (ft, NAVD 88)
Stage and Flow	1.7	BLM Wetland	9/13/2013 / 11:45	4,334.63
	22.8	Below Big Marsh Creek	12/17/2014 / 12:30	4,628.66
	23.5	Above Big Marsh Creek	12/18/2014 / 10:45	4,639.52
Stage	21.9	Below Highway 58 in Wetland near Creek	1/28/2015 /12:30	4,612.03
	21.9	Below Highway 58 in Wetland away from Creek	1/28/2015 / 13:15	4,611.52
	22.8	Wetland below Big Marsh Creek	12/17/2014 / 11:30	4,628.78
Barometric Pressure	1.7	BLM Wetland	9/13/2013 / 11:45	N/A
	22.8	Below Big Marsh Creek	12/17/2014 / 11:30	N/A

4.2.1. Stage Hydrographs

Stage hydrographs for Crescent Creek under regulated conditions in 2015 are shown in Figures 4-12, 4-13, 4-14, and 4-15 at the locations above Marsh Creek (RM 23.5), below Marsh Creek (RM 22.8), near Highway 58 (RM 21.9), and near the confluence with the Little Deschutes River (RM 1.7), respectively. At the RM 22.8 site, the stage hydrographs indicate that the wetland adjacent to Crescent Creek becomes connected to the creek at higher flows (Figure 4-13). The water surface elevations at the two wetland gages at RM 21.9 show very similar patterns, but they have an elevation difference of 0.5 foot or more (Figure 4-14). This suggests the wetlands are hydraulically linked, but the wetland near the creek is upstream of the wetland away from the creek. Data for RM 1.7 (Figure 4-15) stop on November 5, 2015 because the site was not visited in the spring of 2016 due to high stream flows.

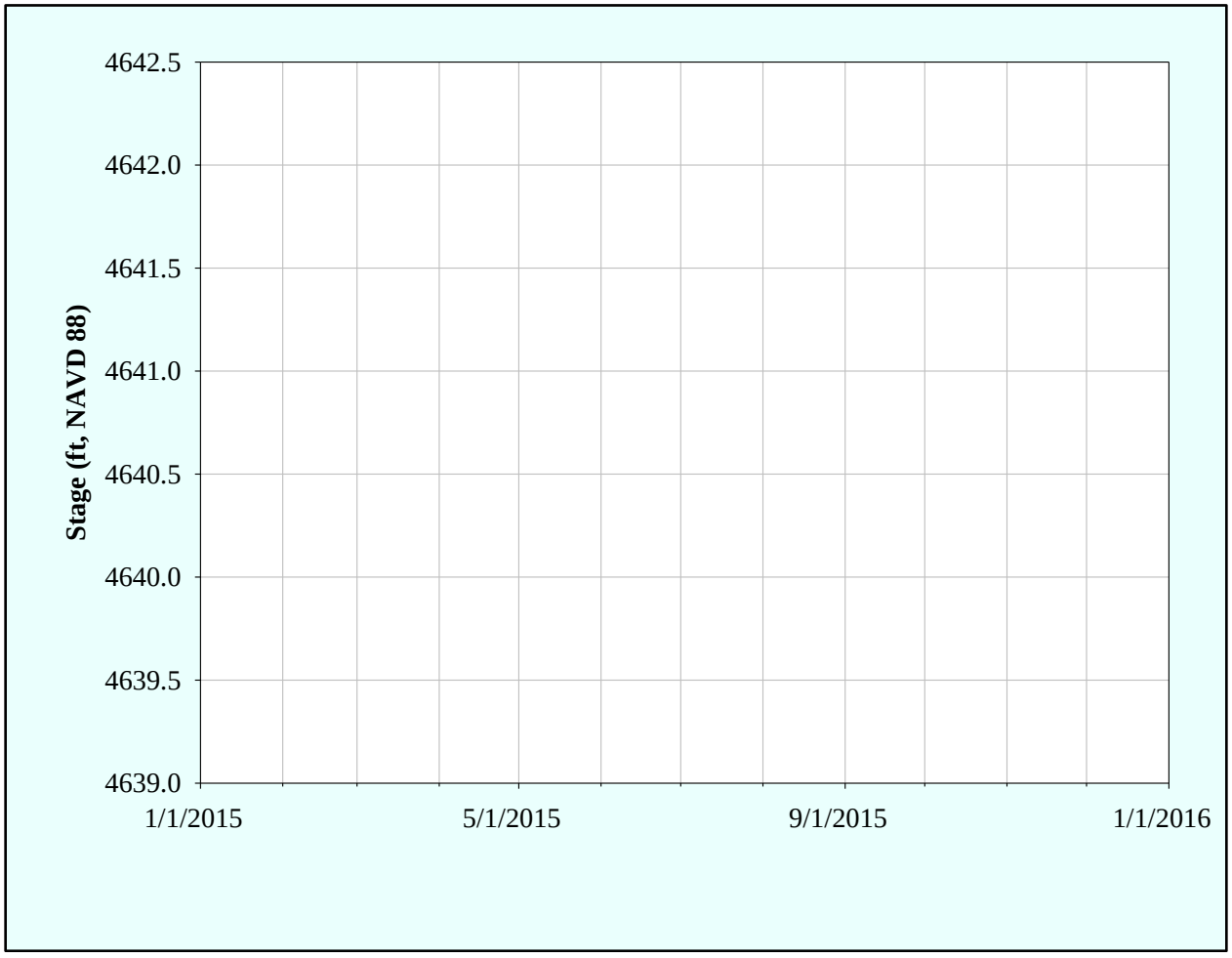

Figure 4-12. Regulated daily stages in Crescent Creek above Big Marsh Creek (RM 23.5), Calendar Year 2015.

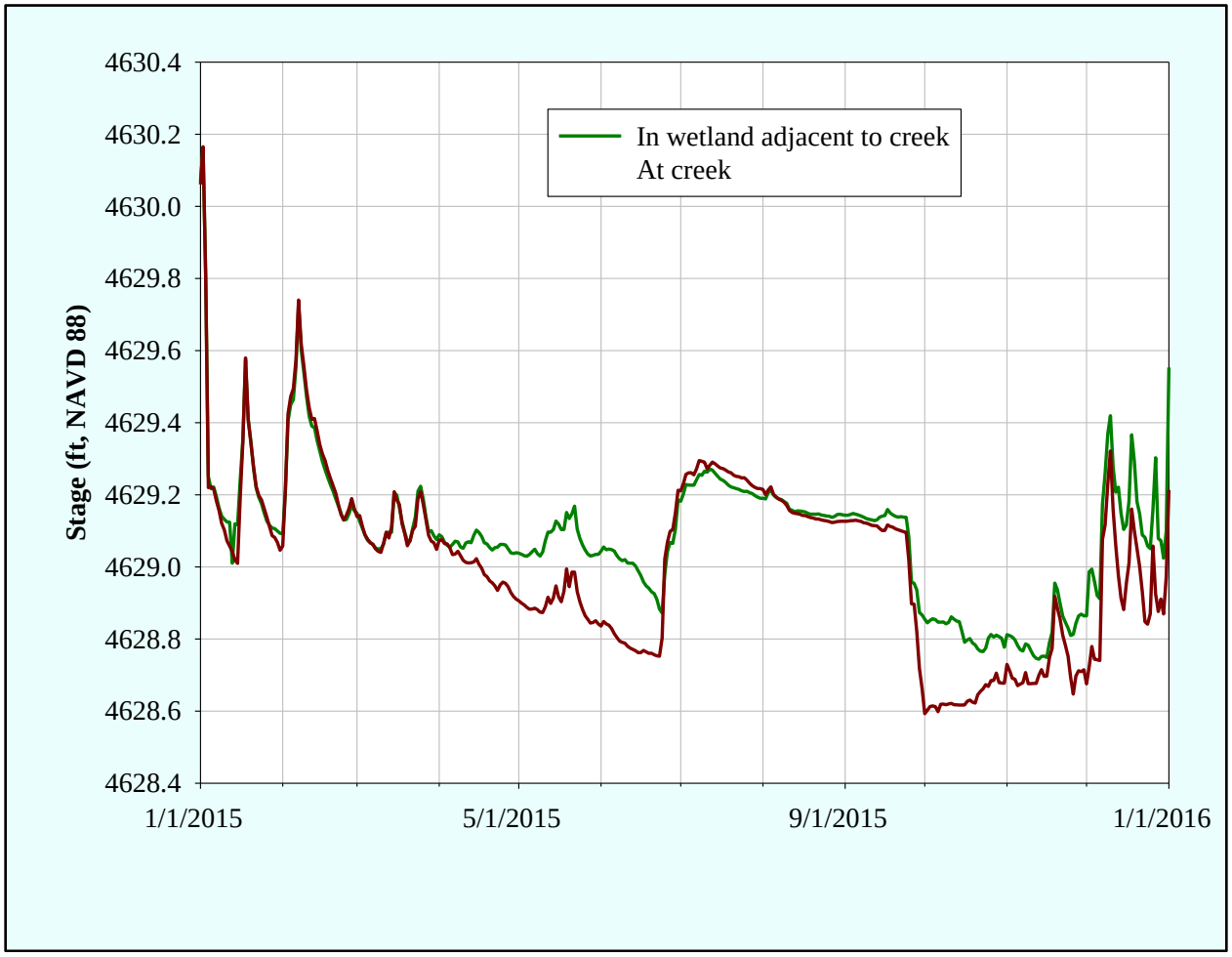

Figure 4-13. Regulated daily stages in Crescent Creek below Big Marsh Creek (RM 22.8), Calendar Year 2015.

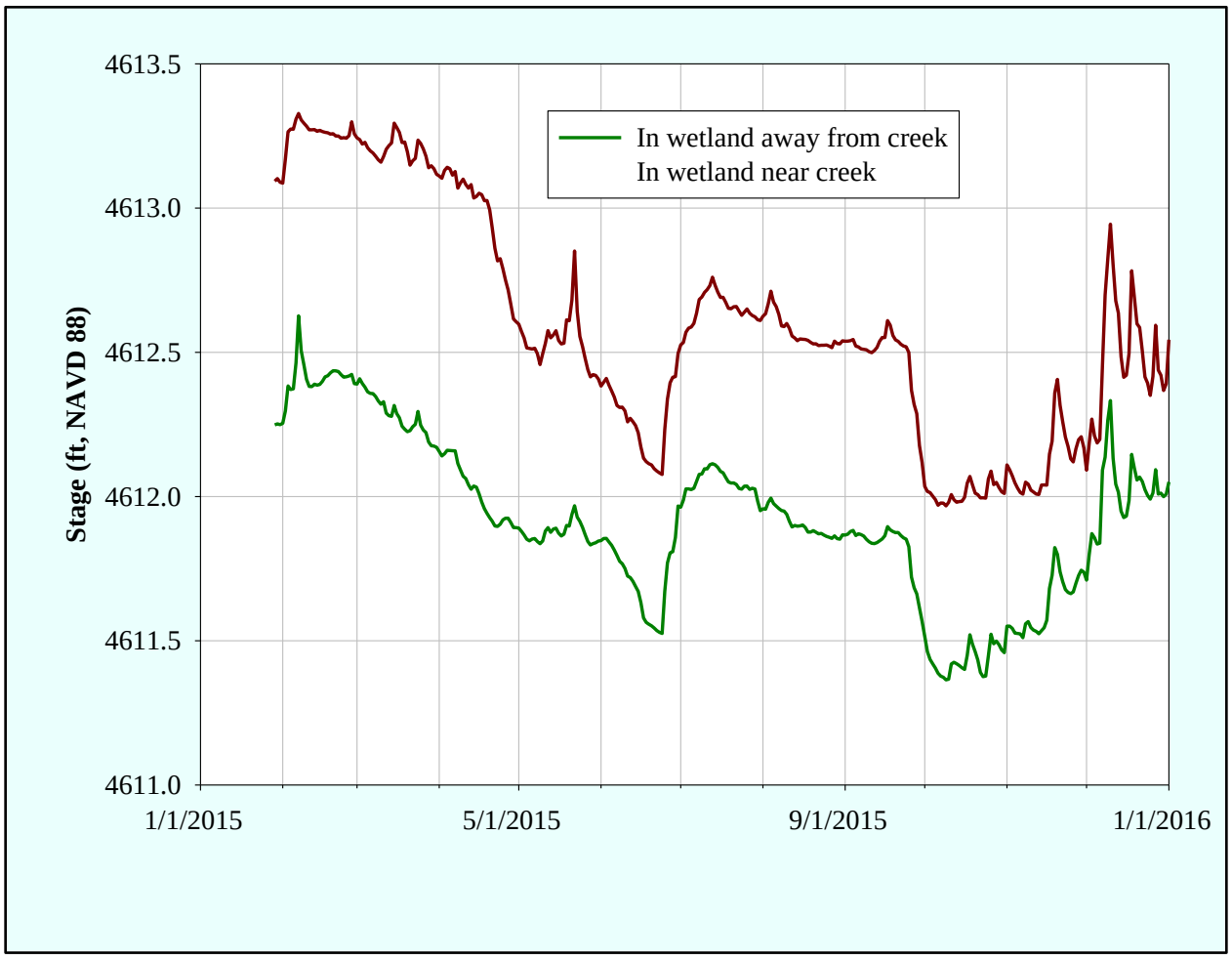

Figure 4-14. Regulated daily stages in Crescent Creek near Highway 58 (RM 21.9), Calendar Year 2015.

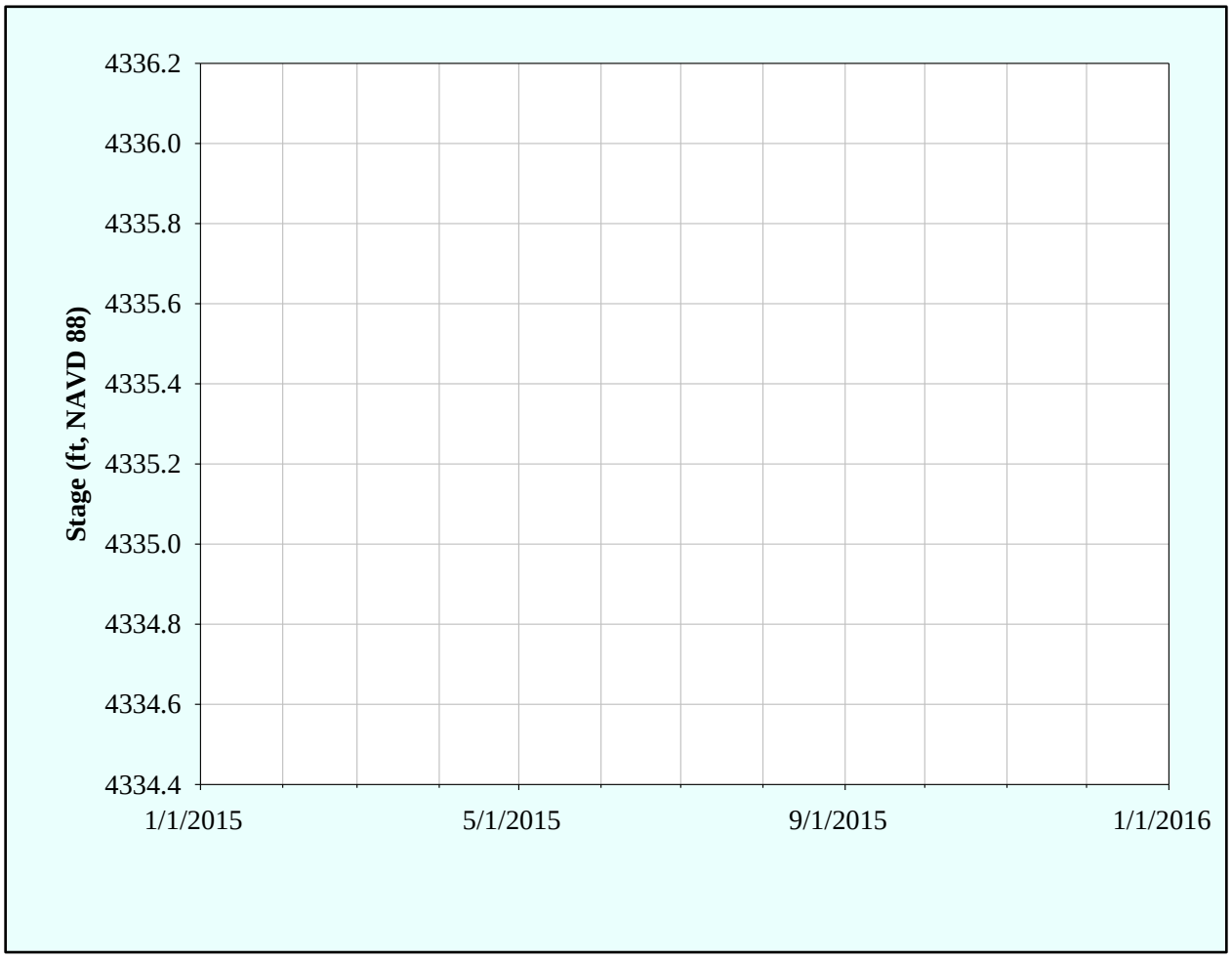

Figure 4-15. Regulated daily stages in Crescent Creek near Bureau of Land Management (BLM) wetland (RM 1.7), Calendar Year 2015.

4.2.2. Stage/Discharge Rating Curves

A summary of flows measured in Crescent Creek at the four locations with new gages is provided in Table 4-3. Also reported in Table 4-3 are the flows reported for Crescent Creek below Crescent Dam (OWRD Gage14060000) and for the Little Deschutes River at La Pine (OWRD Gage 14063000).

Between Crescent Dam and the confluence with Big Marsh Creek the flows in Crescent Creek increase in magnitude from 24 to 34 cfs. There is also an increase in Crescent Creek flow from Big Marsh Creek, and a further increase in flow at the site near Highway 58 (RM 21.9). Flows then remain the same or decrease from RM 21.9 to RM 1.7 (near the confluence with the Little Deschutes River). Between RM 1.7 on Crescent Creek and the Little Deschutes River, flows could either increase or decrease, depending on season (Table 4-3).

The flows and concurrent water surface elevations that were used to develop stage/discharge rating curves for Crescent Creek above Big Marsh Creek, below Big Marsh Creek, and the BLM wetland are listed in Table 4-4.

Table 4-3. Summary of Flows Measured in Crescent Creek and the Little Deschutes River in 2015.

Date	Measured Flows (cfs)					
	Crescent Creek					Little Deschutes River
	Below Crescent Dam	Upstream from Big Marsh Creek (RM 23.5)	Downstream from Big Marsh Creek (RM 22.8)	Wetland (RM 21.9)	Wetland (RM 1.7)	Near La Pine
1/28/2015	16	50	127	134		197
1/29/2015	16				134	191
5/14/2015	28	52	92	93		115
5/15/2015	28				84	121
7/30/2015	131	159	161	166		127
7/31/2015	131				139	127

Table 4-4. Measured Flows and Concurrent Water Surface Elevations Used to Develop Stage/Discharge Rating Curves in Crescent Creek above Big Marsh Creek, below Big Marsh Creek, and at BLM Wetland.

Location	Date/Time	Flow (cfs)	Water Surface Elevation (ft, NAVD 88)
Above Big Marsh Creek (RM 23.5)	1/28/15 / 10:32	49.9	4,639.57
	5/14/2015 / 13:34	52.3	4,639.66
	7/30/2015 / 14:16	158.7	4,640.30
Below Big Marsh Creek (RM 22.8)	1/28/15 / 16:26	127.3	4,629.11
	5/14/2015 / 15:06	91.8	4,628.93
	7/30/2015 / 15:40	161.4	4,629.23
BLM Wetland (RM 1.7)	1/29/15 / 13:44	134.1	4,335.18
	5/15/2015 / 9:37	83.8	4,334.85
	7/31/2015 / 9:45	138.6	4,335.16

The stage/discharge rating curve developed for Crescent Creek above Big Marsh Creek is shown in Figure 4-16. It is based on Equation 4-1.

Equation 4-1: $$\boldsymbol{Q = 46.9 * (WSE - 4638.57)^{2.19}}$$

Where $\boldsymbol{Q}$ = flow (cfs)
$\boldsymbol{WSE}$ = water surface elevation (ft)

The stage/discharge rating curve developed for Crescent Creek below Big Marsh Creek is shown in Figure 4-17. It is based on Equation 4-2.

Equation 4-2: $$\boldsymbol{Q = 48.0 * (WSE - 4627.65)^{2.62}}$$

The stage/discharge rating curve developed for Crescent Creek near the confluence with Little Deschutes River is shown in Figure 4-18. It is based on Equation 4-3.

Equation 4-3: $$\boldsymbol{Q = 37.5 * (WSE - 4333.45)^{2.38}}$$

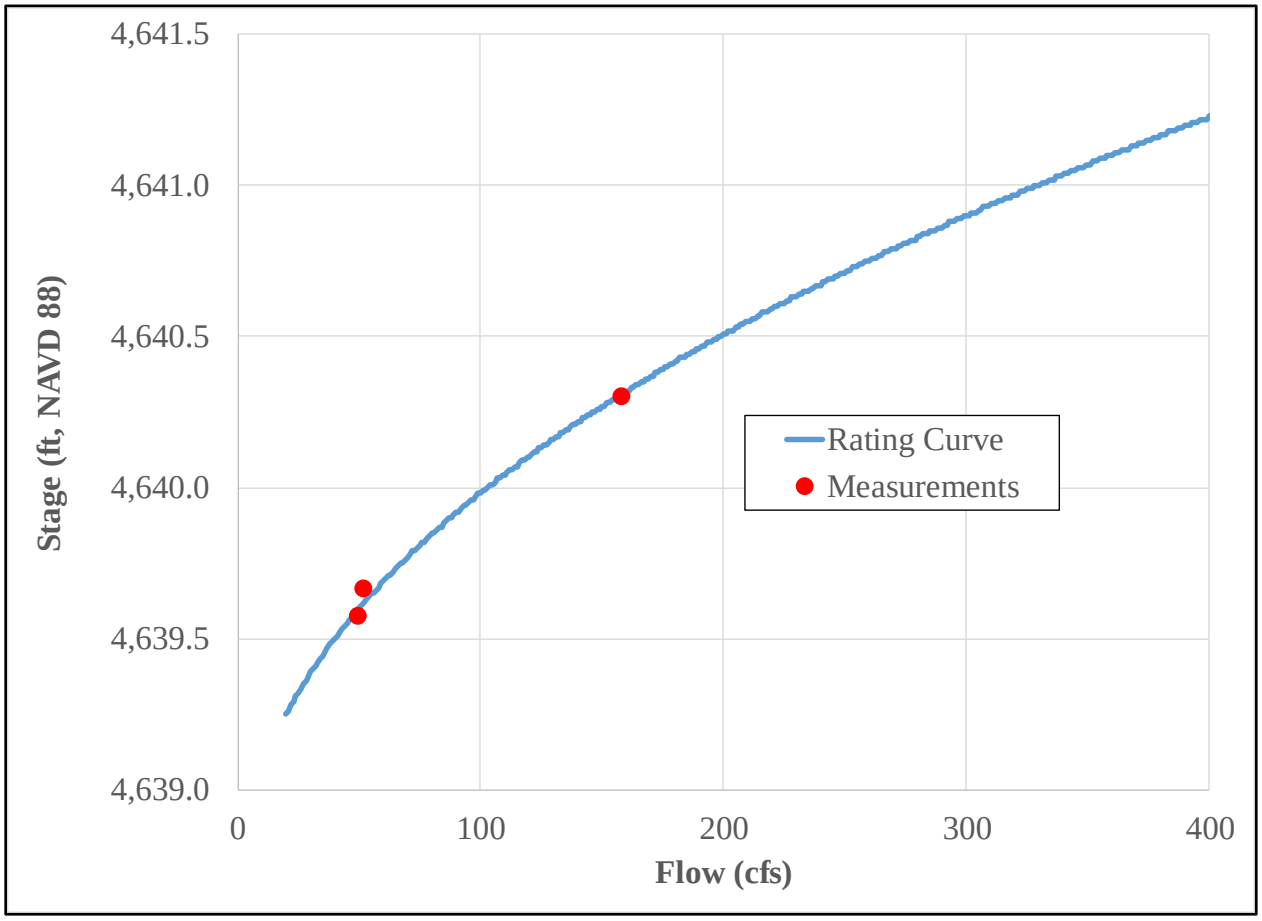

Figure 4-16. Stage/discharge rating curve for Crescent Creek above Big Marsh Creek (RM 23.5).

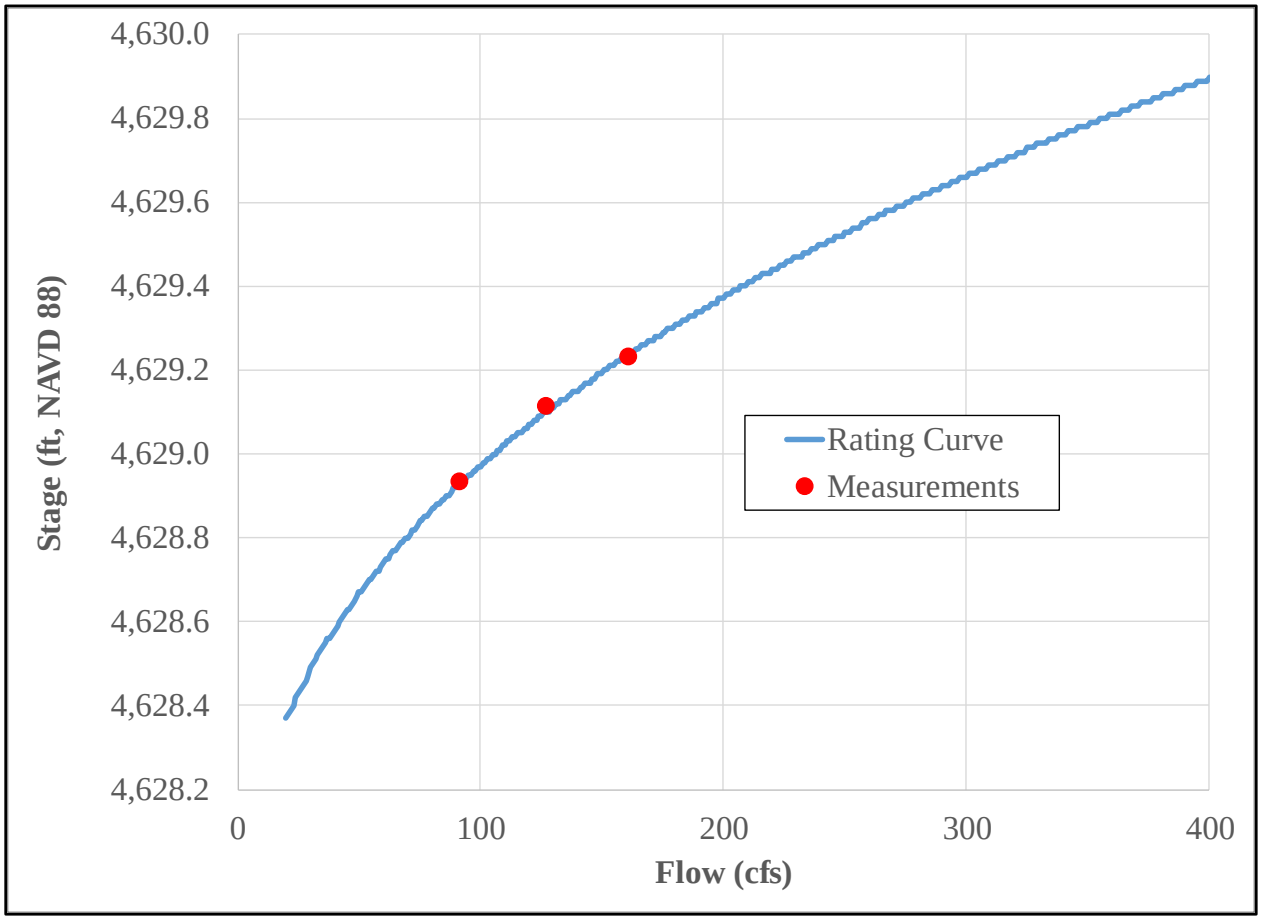

Figure 4-17. Stage/discharge rating curve for Crescent Creek below Big Marsh Creek (RM 22.8).

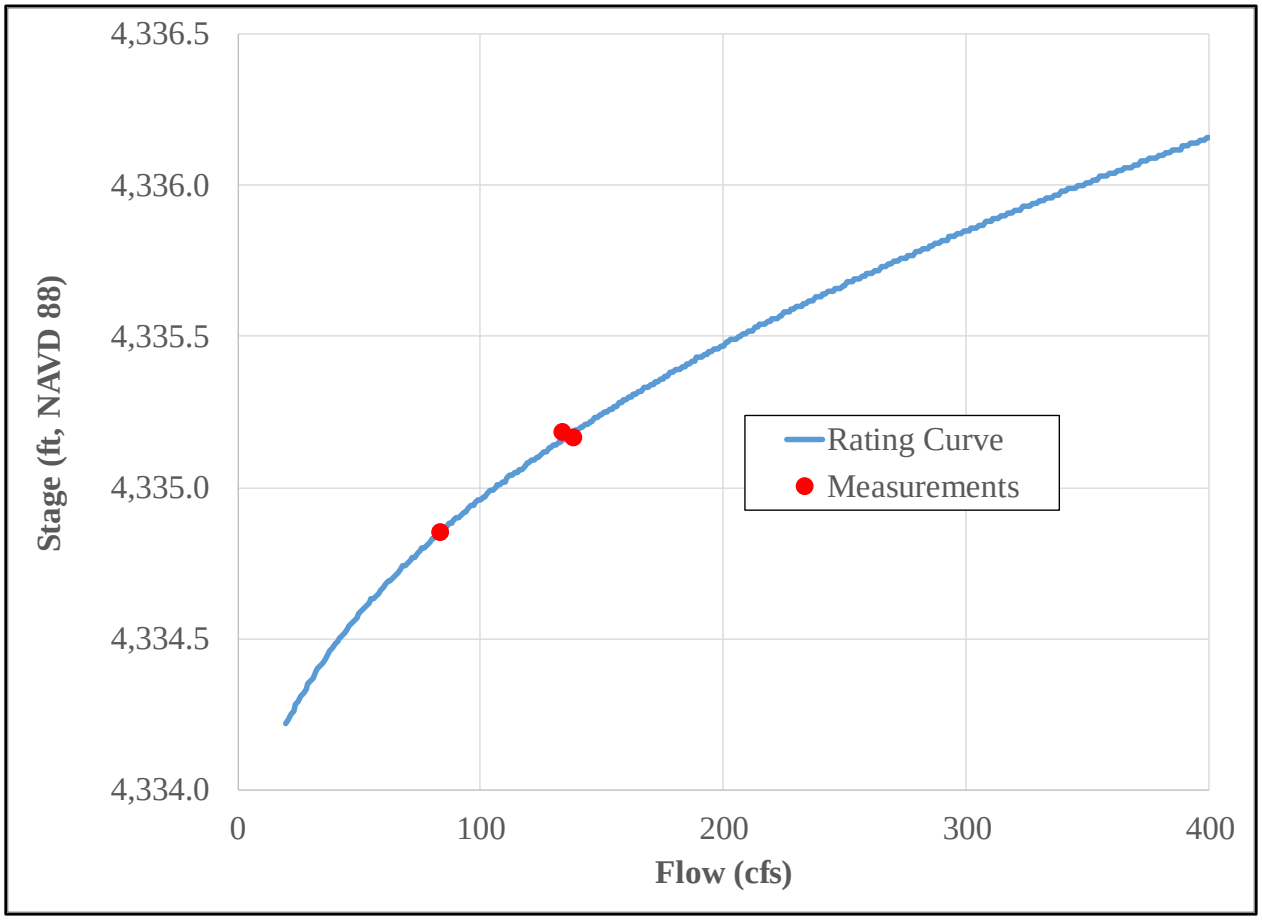

Figure 4-18 Stage/discharge rating curve for Crescent Creek near confluence with Little Deschutes River (RM 1.7).

4.2.3. Flow Hydrographs

The stage/discharge rating curves developed in Section 4.2.2 were applied to the stage hydrographs shown in Section 4.2.1 to derive the flow hydrographs shown in Figure 4-19. Daily flows in Crescent Creek above Big Marsh Creek, below Big Marsh Creek, and near the confluence with the Little Deschutes River are shown in Figure 4-19 for Calendar Year 2015.

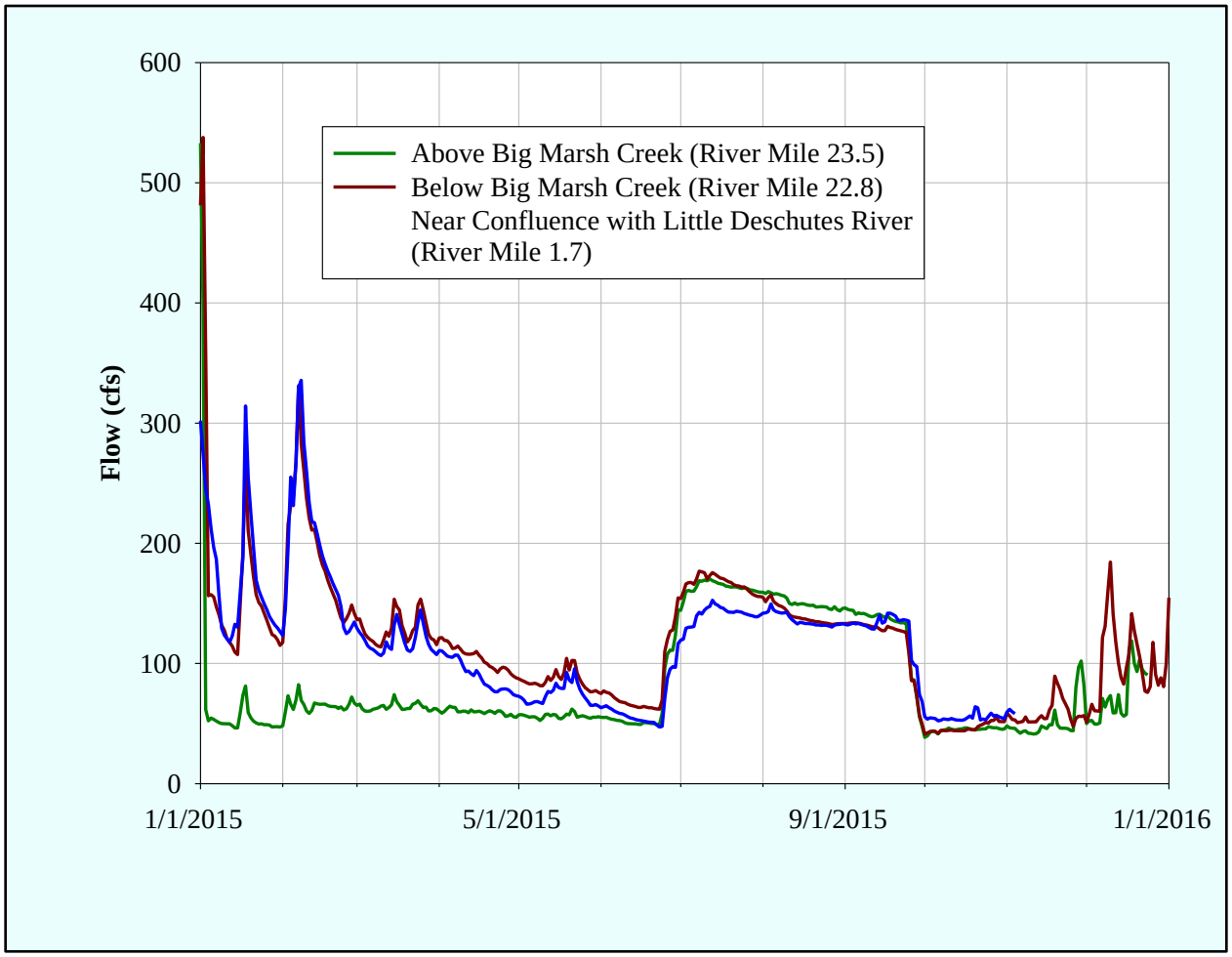

Figure 4-19. Regulated daily flows in Crescent Creek above Big Marsh Creek (RM 23.5), below Big Marsh Creek (RM 22.8), and near confluence with Little Deschutes River (RM 1.7), Calendar Year 2015.

4.2.4. Comparison of Regulated and Unregulated Conditions

Comparisons of regulated and unregulated conditions are provided in this section for Crescent Creek below Crescent Dam, above Big Marsh Creek, below Big Marsh Creek, and near the confluence with the Little Deschutes River, and also for the Little Deschutes River. Stage hydrographs are provided in Section 4.2.4.1 and flow hydrographs are provided in Section 4.2.4.2.

4.2.4.1. Stage Hydrographs

Regulated and unregulated stage hydrographs for Crescent Creek below Crescent Dam in Calendar Year 2015 are shown in Figure 4-20. Interim operations (minimum year-round flow release of 30 cfs) began on February 12, 2015. Regulated water surface elevations were higher than unregulated elevations from April through mid-November and consistently lower than unregulated elevations only during January and early February when unregulated flows peaked due to winter storms. During the summer months (July, August, and September), the regulated water surface elevations were over 1 foot higher than the unregulated elevations.

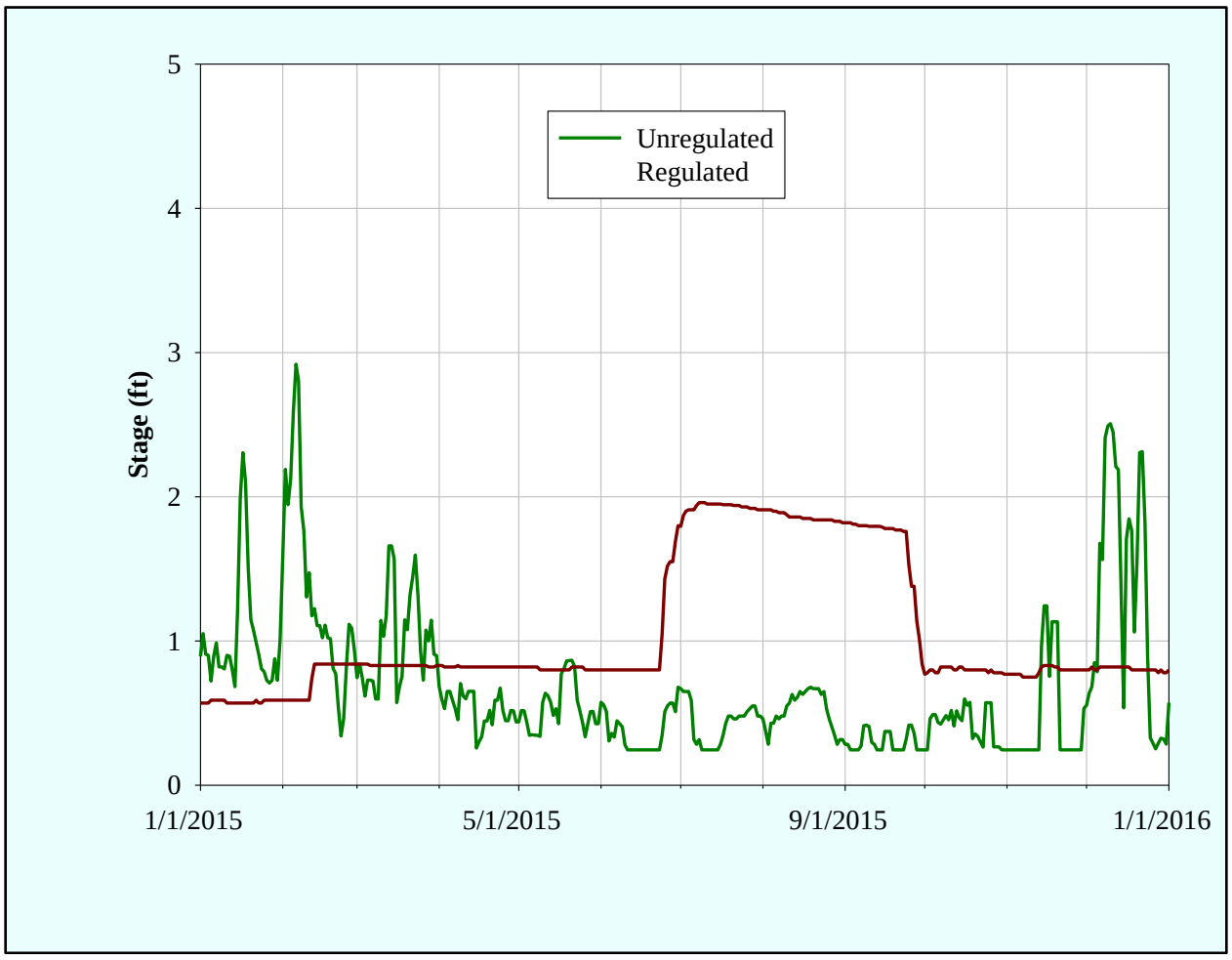

Figure 4-20. Unregulated and regulated daily stages in Crescent Creek below Crescent Dam, Calendar Year 2015.

Regulated and unregulated stage hydrographs for Crescent Creek above Big Marsh Creek in Calendar Year 2015 are shown in Figure 4-21. The patterns are similar to those for Crescent Creek below Crescent Dam. Regulated water surface elevations were higher and more consistent than unregulated elevations in April through mid-November. During the summer months (July, August, and September), the regulated water surface elevations were almost 1 foot higher than the unregulated water surface elevations.

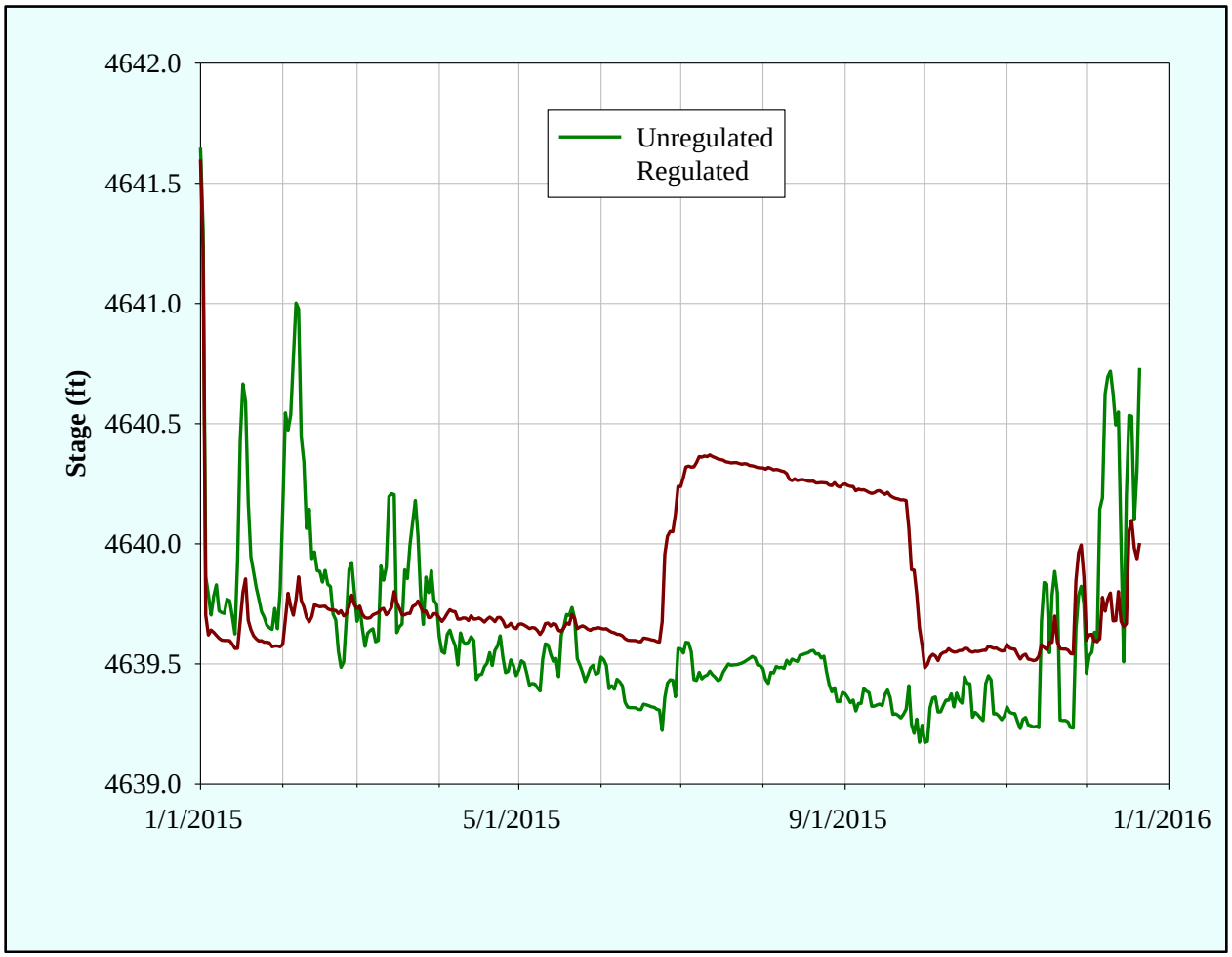

Figure 4-21. Unregulated and regulated daily stages in Crescent Creek above Big Marsh Creek (RM 23.5), Calendar Year 2015.

Regulated and unregulated stage hydrographs for Crescent Creek below Big Marsh Creek in Calendar Year 2015 are shown in Figure 4-22. Regulated and unregulated water surface elevations were similar from November through March, except that unregulated elevations increased for brief periods during rain events. From April through mid-November, regulated water surface elevations were higher than unregulated elevations. In July, August, and September, the regulated water surface elevations were almost 1 foot higher than the unregulated elevations.

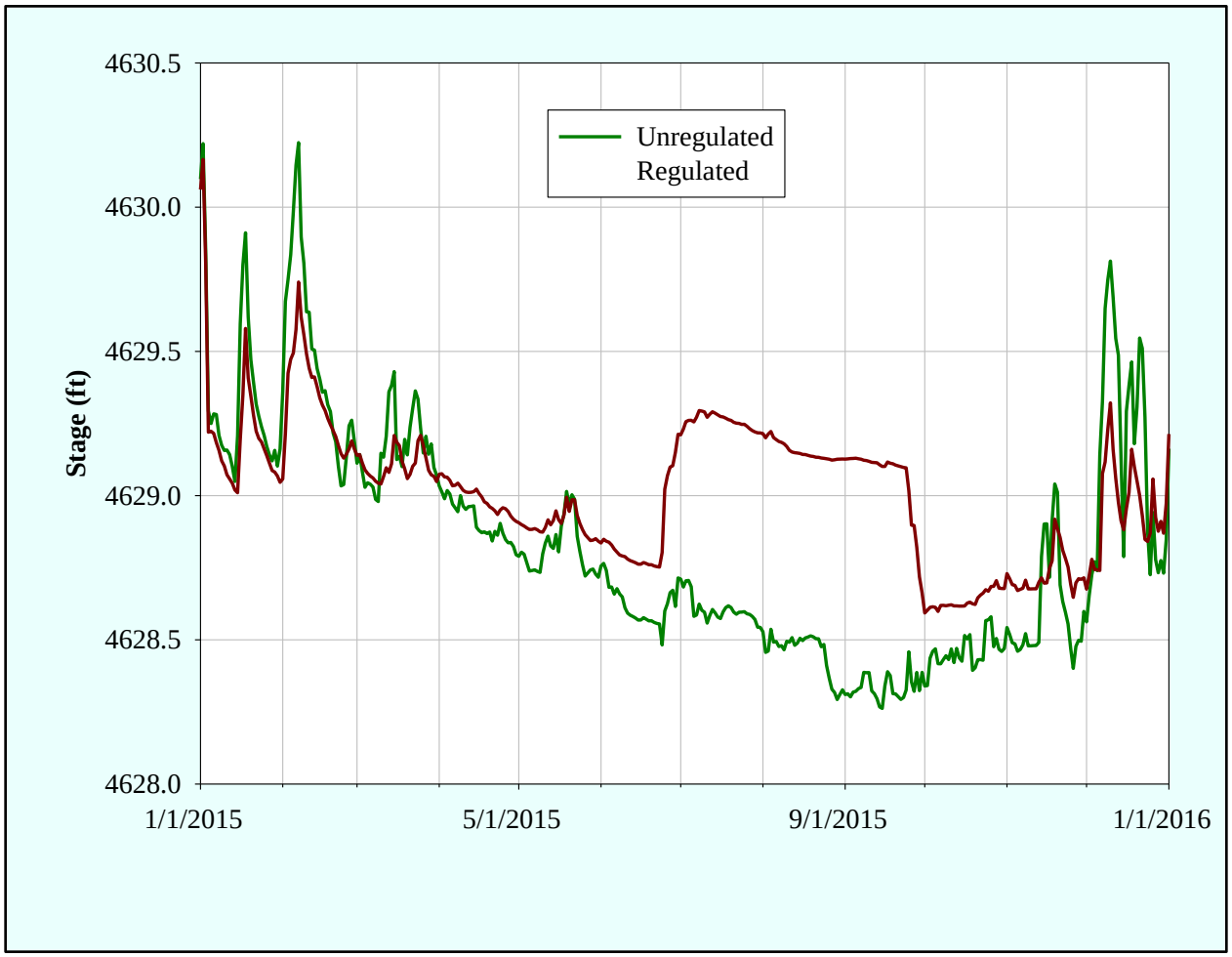

Figure 4-22. Unregulated and regulated daily stages in Crescent Creek below Big Marsh Creek (RM 22.8), Calendar Year 2015.

Regulated and unregulated stage hydrographs for Crescent Creek near the confluence with the Little Deschutes River in Calendar Year 2015 are shown in Figure 4-23. As with other locations on Crescent Creek downstream from the confluence with Big Marsh Creek, regulated water surface elevations were similar to unregulated elevations in January through March, except for short-term peaks that occurred for unregulated elevations. From April through October, regulated water surface elevations were consistently higher than unregulated elevations. During the summer months (July, August, and September), the regulated water surface elevations were again almost 1 foot higher than the unregulated water surface elevations. As noted previously, data for November and December at RM 1.7 were not collected (the instrument was not downloaded) due to access limitations in early 2016.

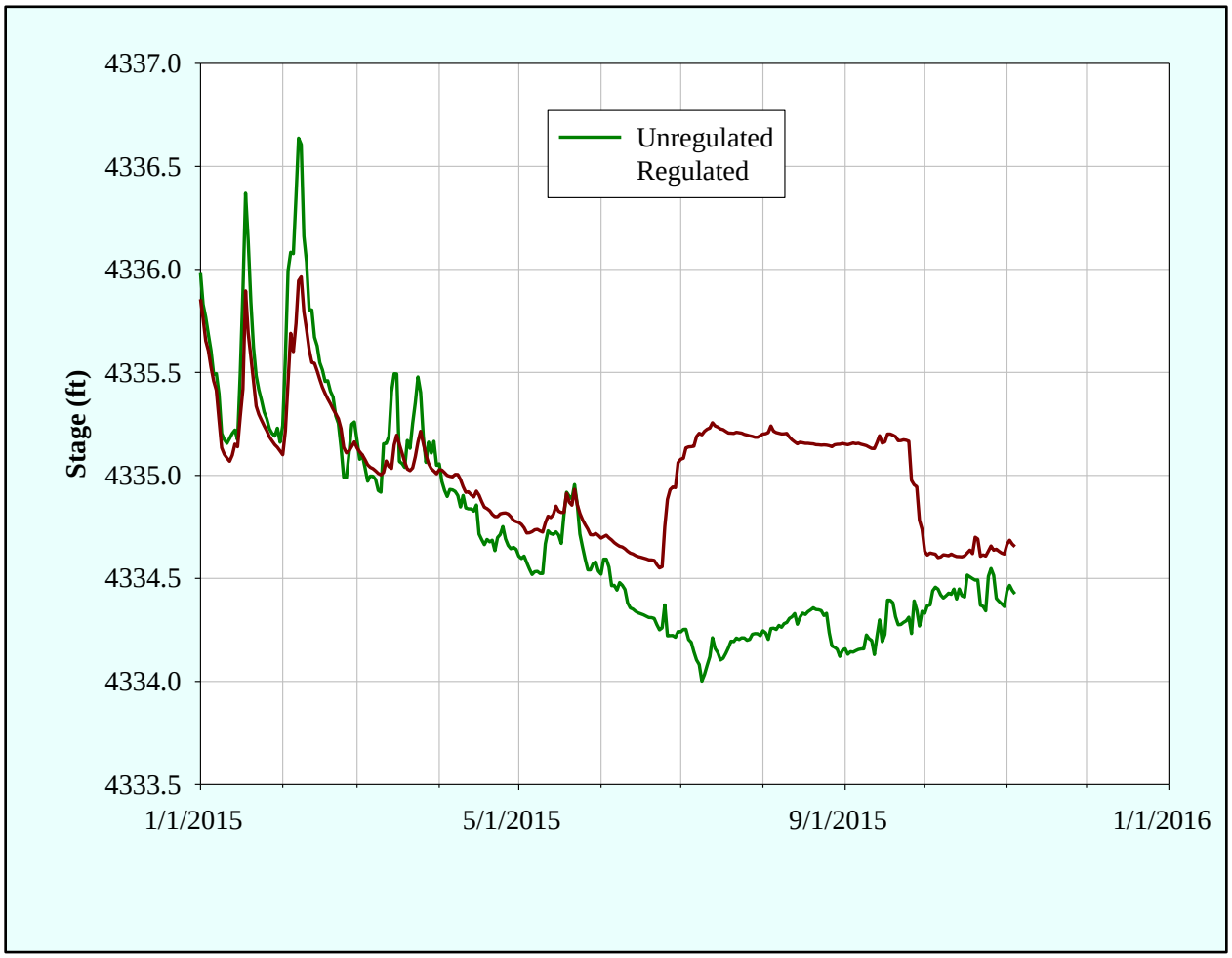

Figure 4-23. Unregulated and regulated daily stages in Crescent Creek near confluence (RM 1.7), Calendar Year 2015.

Regulated and unregulated stage hydrographs for the Little Deschutes River at La Pine in Calendar Year 2015 are shown in Figure 4-24. The pattern is very similar to that observed for Crescent Creek RM 1.7. Regulated and unregulated water surface elevations showed little difference in January through March, as well as in late November and December. Regulated water surface elevations were about 1.5 feet higher than unregulated elevations during the summer months (July through mid-October).

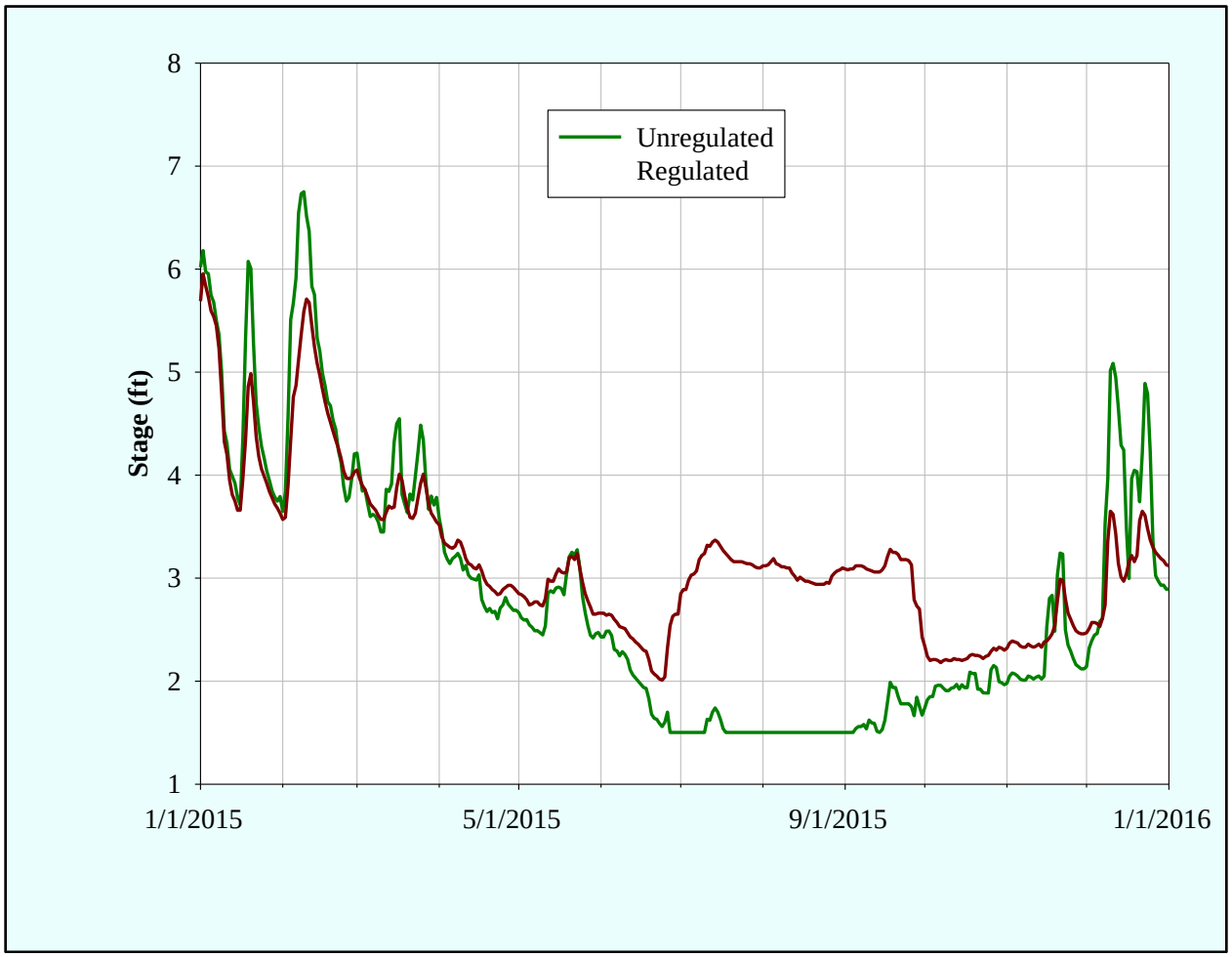

Figure 4-24. Unregulated and regulated daily stages in Little Deschutes River at La Pine, Calendar Year 2015.

4.2.4.2. Flow Hydrographs

Regulated and unregulated flow hydrographs for the four gage locations on Crescent Creek and the Little Deschutes River at La Pine in Calendar Year 2015 are compared in Figures 4-25 through 4-29. Trends in flow mimic those for water surface elevation described in Section 4.2.4.1. Regulated flows were consistently higher that unregulated flows at all locations from April through mid-November. The differences between regulated and unregulated flows were most pronounced in July through September when water was being released from Crescent Lake for irrigation and regulated flows were about 110 to 140 cfs higher than the unregulated flows. The relative difference between regulated and unregulated flows diminished with increasing distance downstream from Crescent Dam.

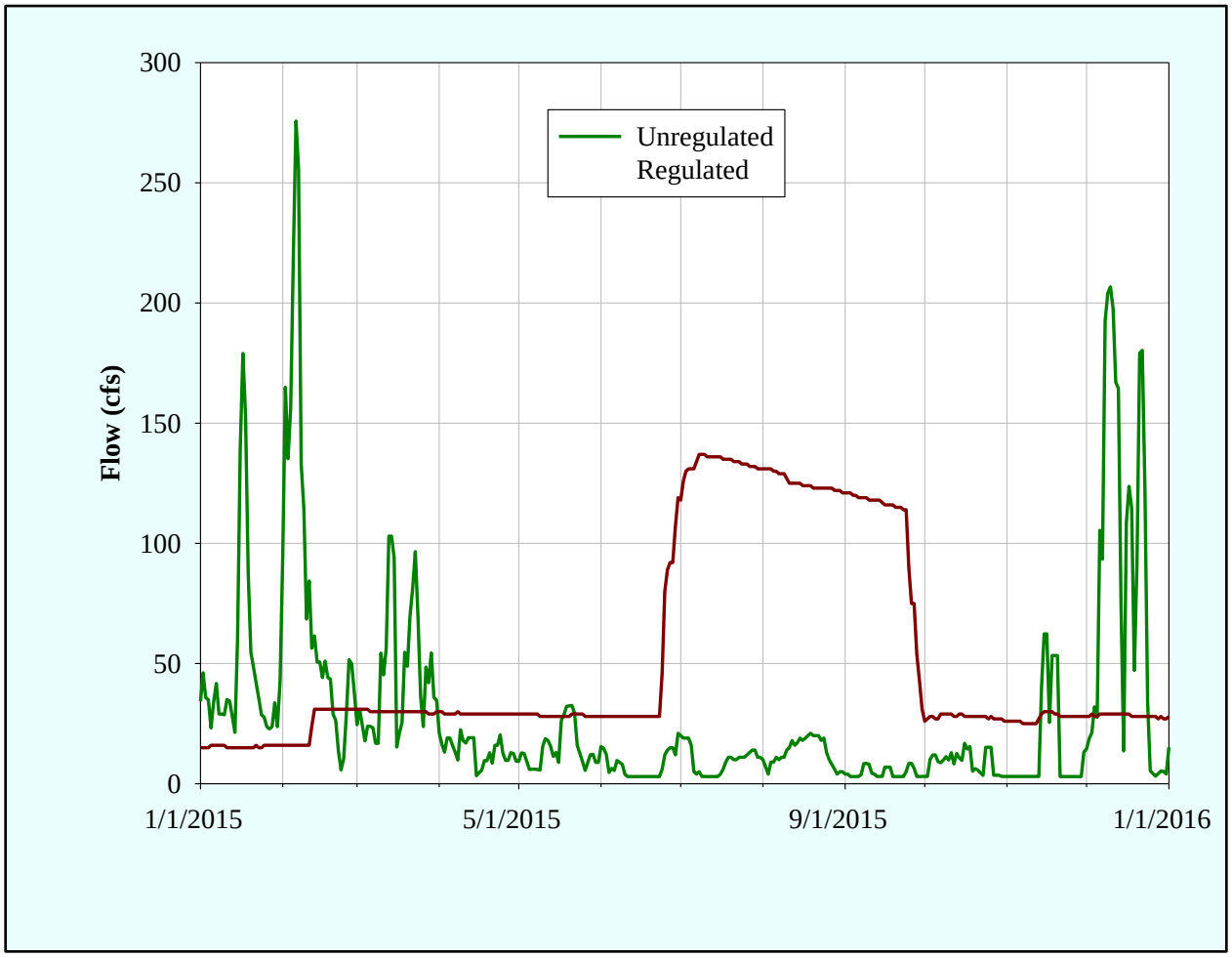

Figure 4-25. Unregulated and regulated daily flows in Crescent Creek below Crescent Dam, Calendar Year 2015.

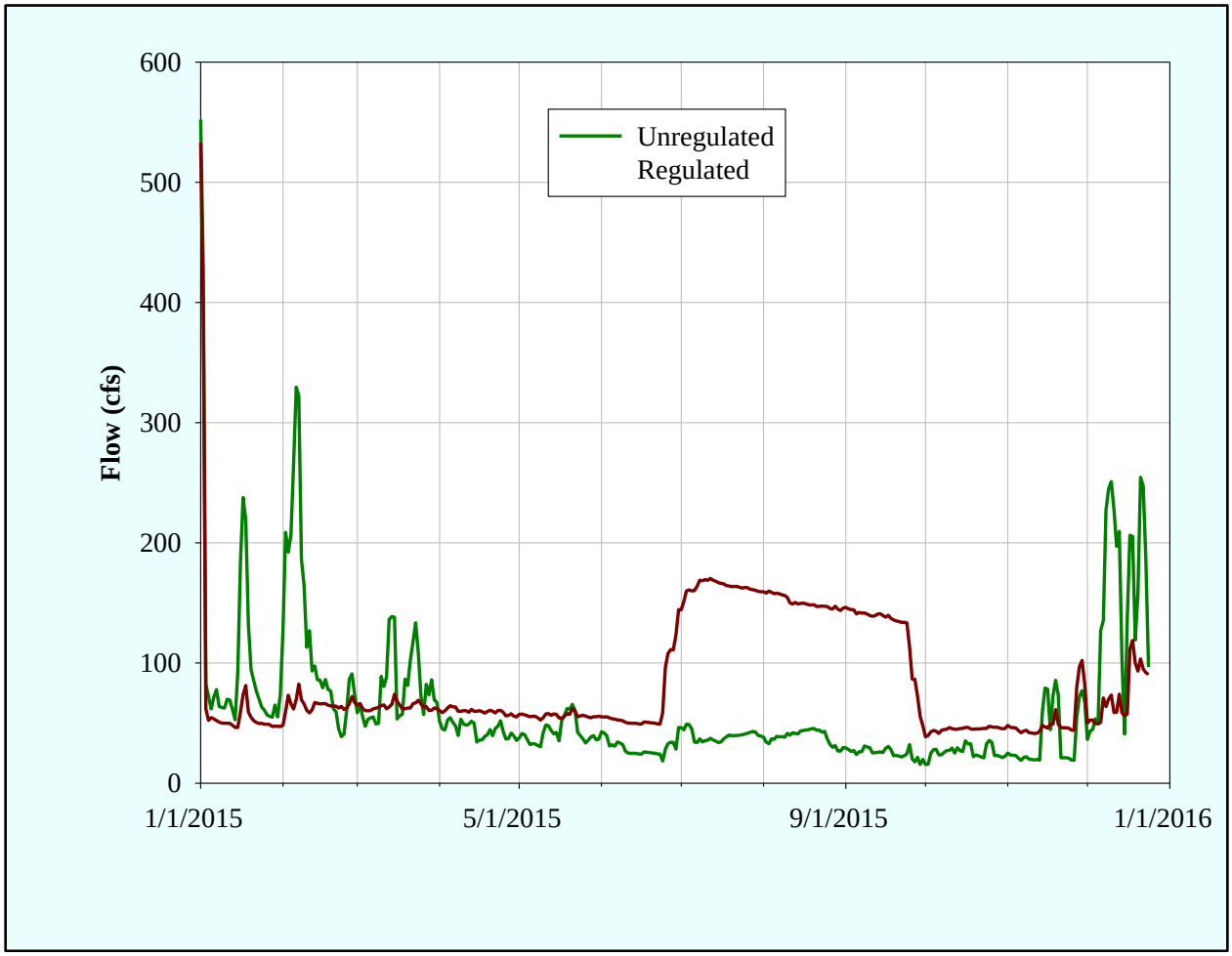

Figure 4-26. Unregulated and regulated daily flows in Crescent Creek above Big Marsh Creek (RM 23.5), Calendar Year 2015.

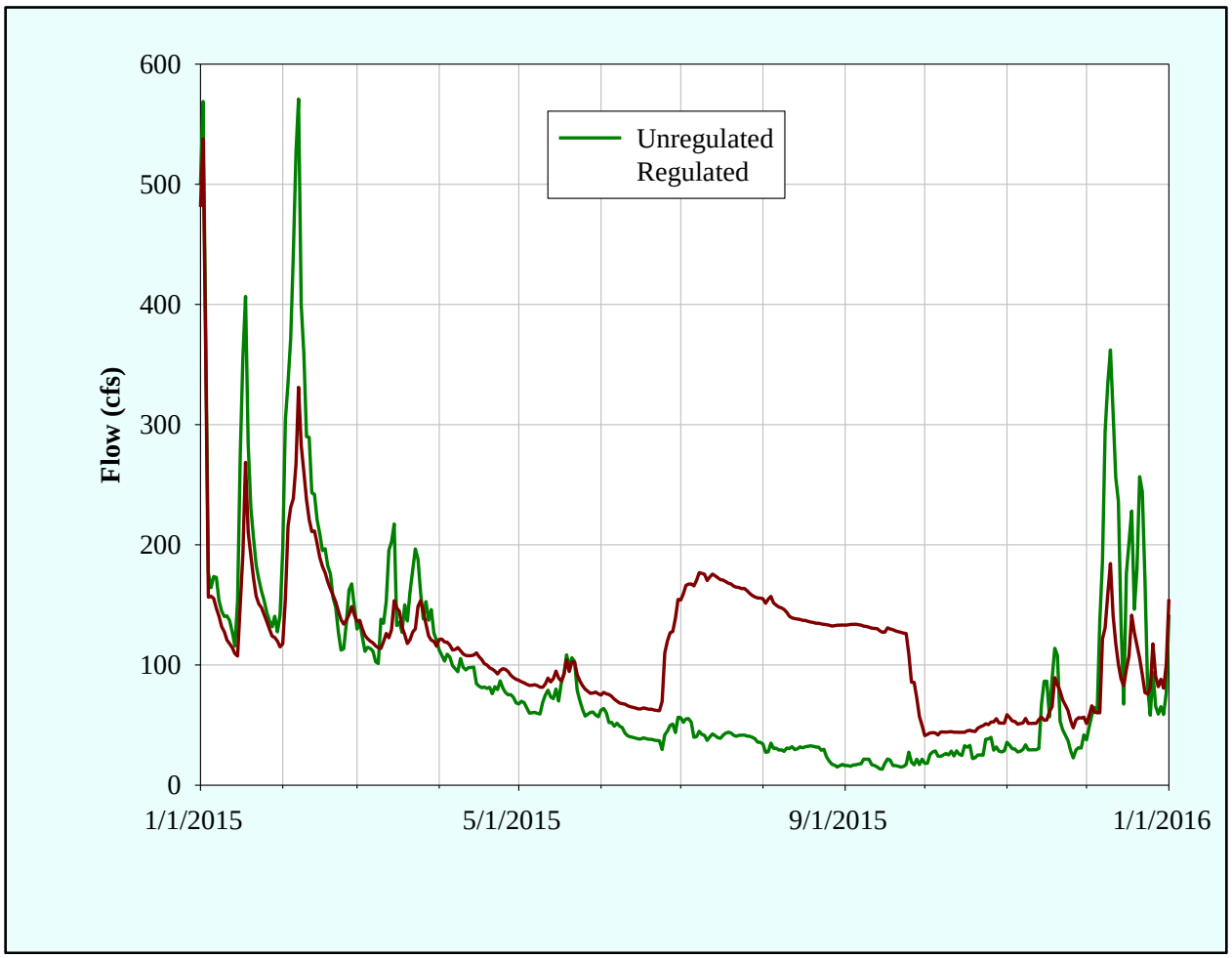

Figure 4-27. Unregulated and regulated daily flows in Crescent Creek below Big Marsh Creek (RM 22.8), Calendar Year 2015.

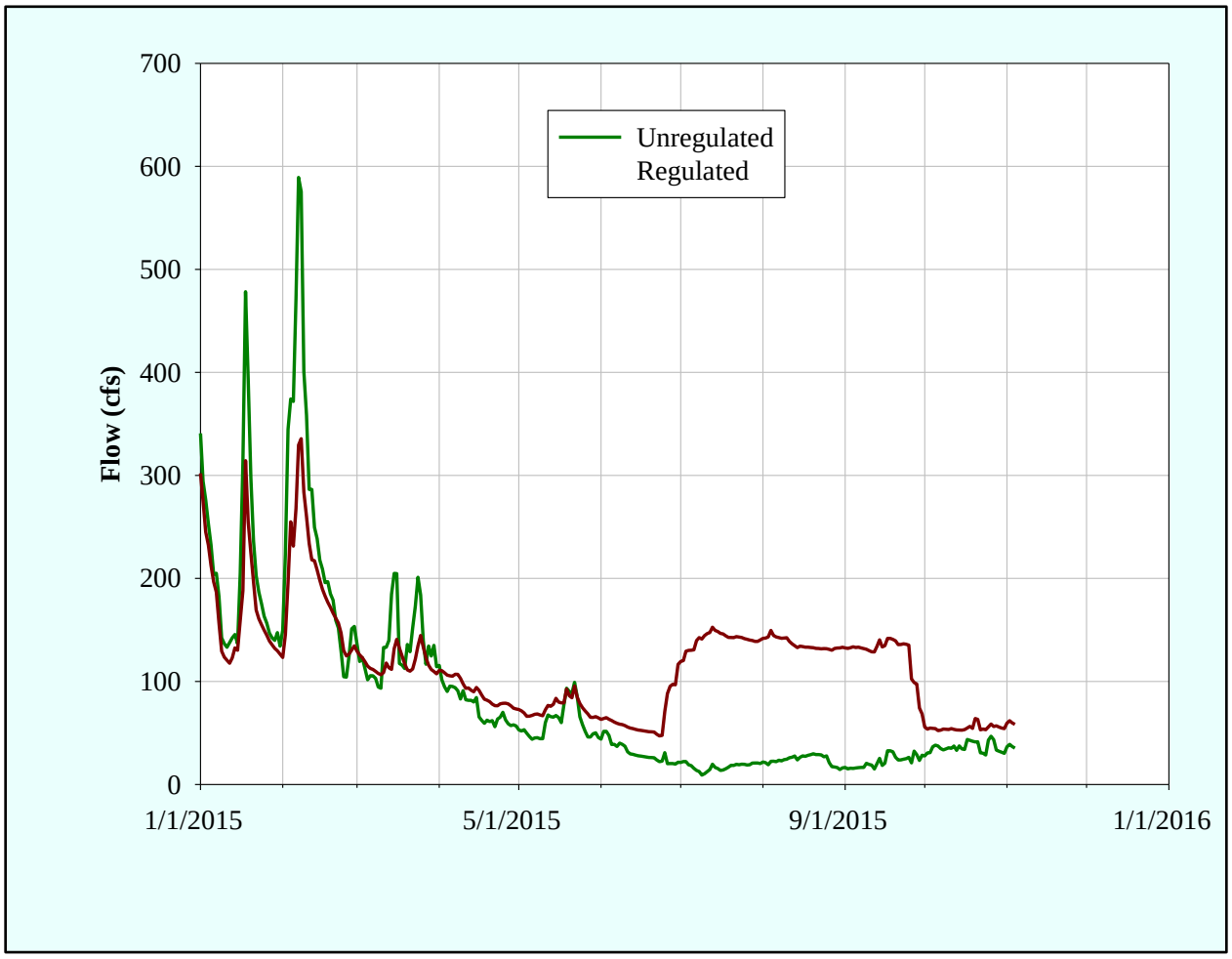

Figure 4-28. Unregulated and regulated daily flows in Crescent Creek near confluence with Little Deschutes River (RM 1.7), Calendar Year 2015.

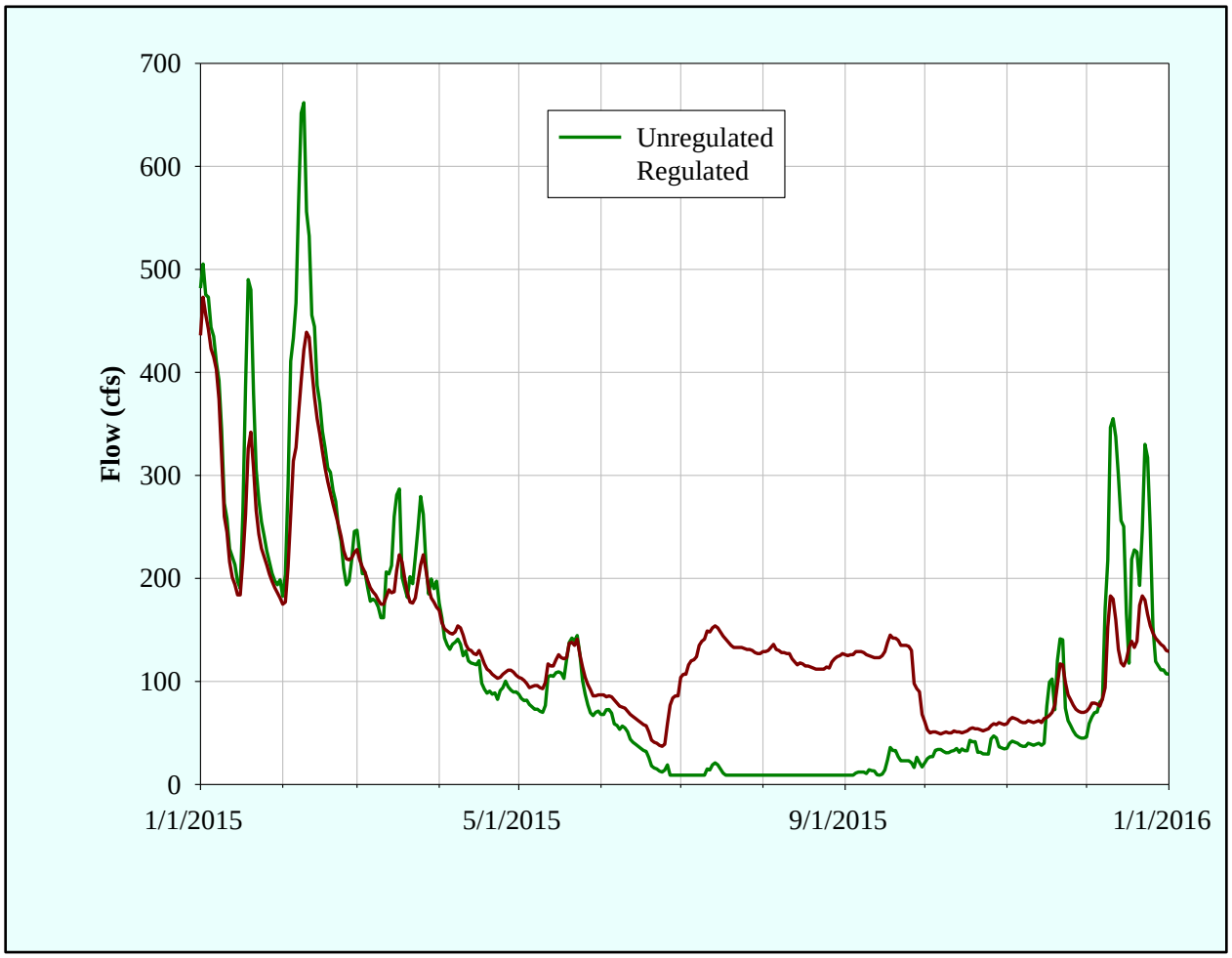

Figure 4-29. Unregulated and regulated daily flows in Little Deschutes River at La Pine, Calendar Year 2015.

5.0 Discussion and Conclusions

For each day of the year, the median daily flows were determined from the 32 Calendar Years from 1983 through 2014. This was done for regulated and unregulated flow conditions in Crescent Creek below Crescent Dam. The results are shown in Figure 5-1, along with regulated and unregulated flows for 2015. Typical historical seasonal patterns of operation of Crescent Lake can be determined from these flow hydrographs. Crescent Lake Reservoir typically stored water from October through June, and then released water from July through September. Under interim operations in 2015, similar seasonal patterns were followed, except that regulated flows during the storage season in 2015 were above the regulated historical median.

It is noteworthy that unregulated flows in 2015 were considerably above the unregulated historical medians in January, February, March and December and below unregulated historical medians in all other months, demonstrating the high degree of natural variation in flows within the Crescent Creek Basin.

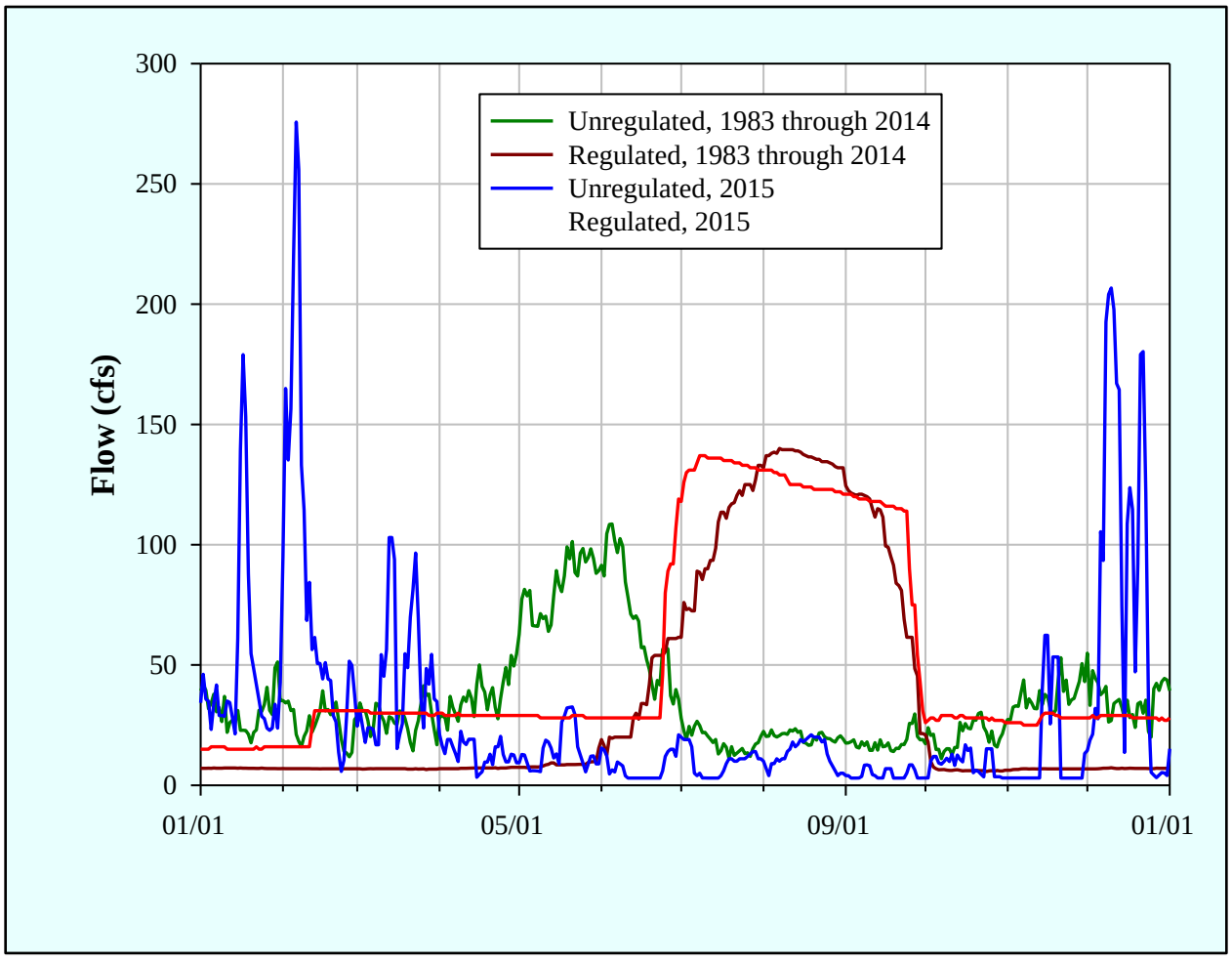

Figure 5-1. Seasonal patterns of median daily flows in Crescent Creek below Crescent Dam under unregulated and regulated flow conditions, 1983 through 2014, and unregulated and regulated daily flows at the same location under interim operations in 2015.

The stage/discharge rating curve shown in Figure 4-6 was used to derive seasonal patterns of median daily stages in Crescent Creek below Crescent Dam (Figure 5-2). The seasonal patterns of median daily stages in Figure 5-2 are similar to the seasonal patterns of median daily flows shown in Figure 5-1. This seasonal pattern was also apparent under interim operations in 2015 (Figure 5-2), except that regulated stages under interim operations were roughly 0.4 foot higher than the historical median during the storage season.

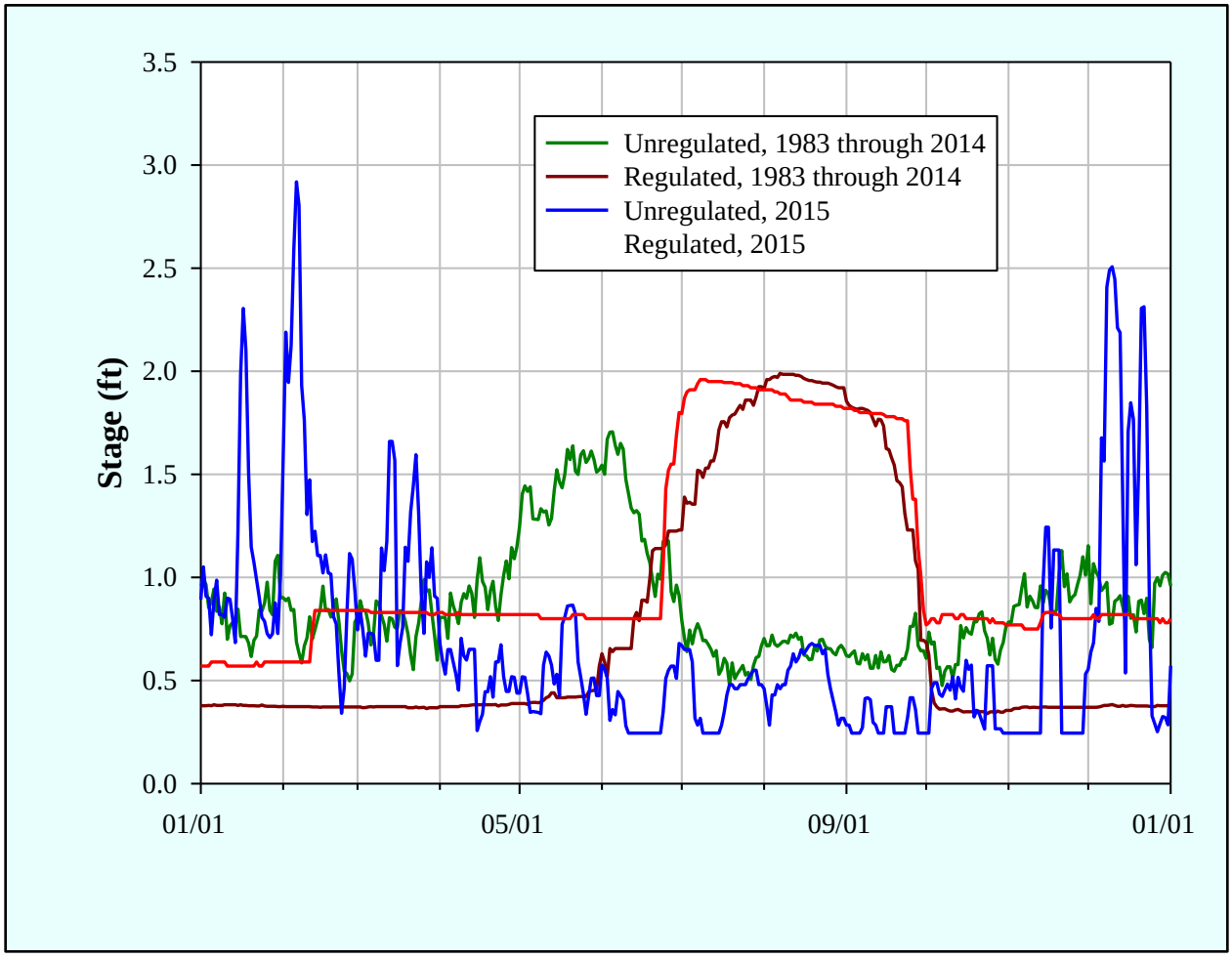

Figure 5-2. Seasonal patterns of median daily stages in Crescent Creek below Crescent Dam under unregulated and regulated flow conditions, 1983 through 2014, and unregulated and regulated daily stages at the same location under interim operations in 2015.

Historical median daily flows and stages were also determined for the Little Deschutes River at La Pine (Figures 5-3 and 5-4). The seasonal patterns at La Pine were similar to those at Crescent Creek below Crescent Dam, but the differences between regulated and unregulated flows at La Pine were relatively small during the storage season. The most notable difference between regulated and unregulated median daily flows was during the months of July, August and September when irrigation releases from Crescent Lake increased the flow at La Pine by about 110 to 140 cfs (Figure 5-3) and increased the stage by over 1.5 foot (Figure 5-4). The seasonal patterns under interim operations in 2015 were similar (Figures 5-3 and 5-4), with the exception that regulated flows were higher than unregulated flows a greater percentage of the year in 2015.

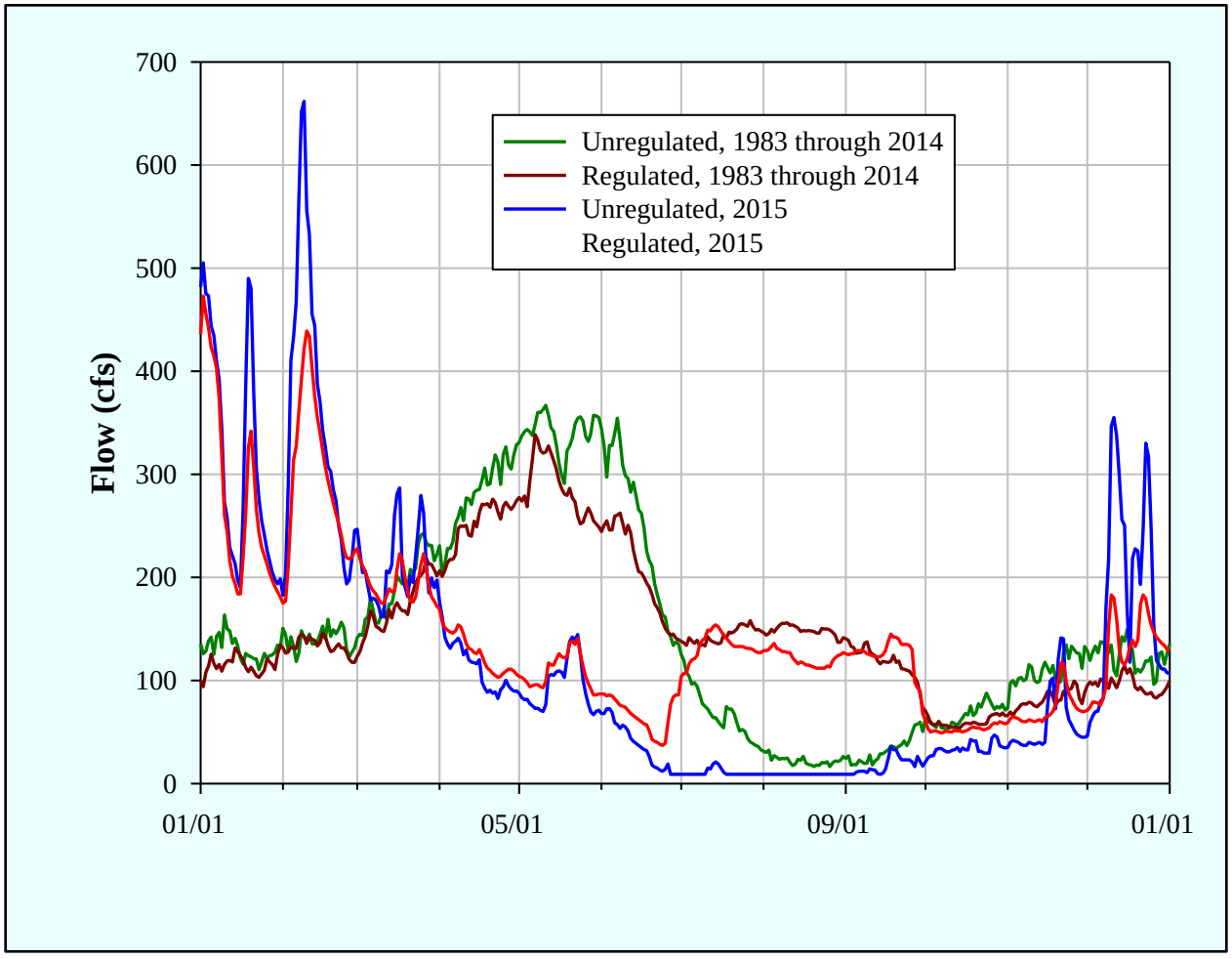

Figure 5-3. Seasonal patterns of median daily flows in the Little Deschutes River at La Pine under unregulated and regulated flow conditions, 1983 through 2014, and unregulated and regulated daily flows at the same location under interim operations in 2015.

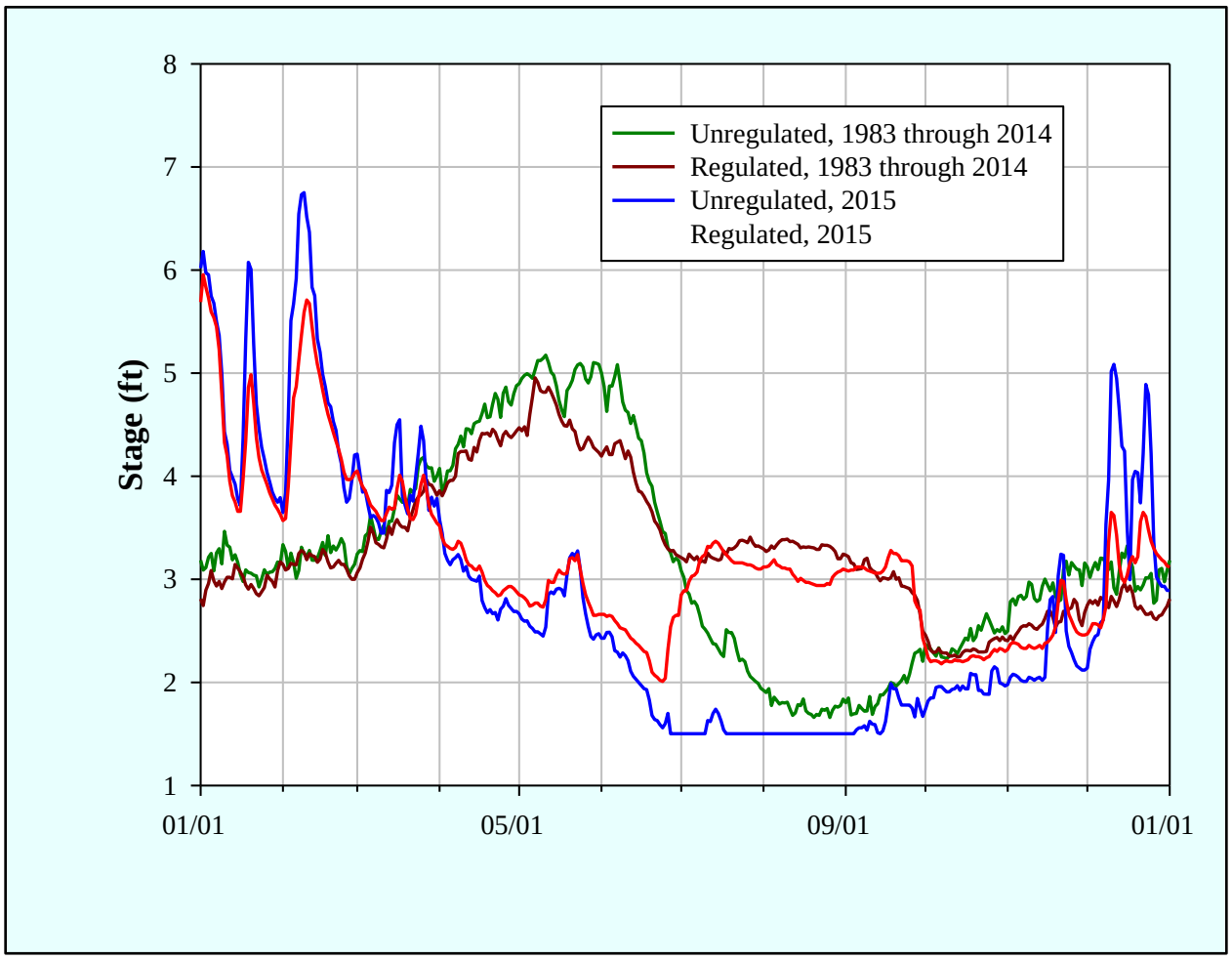

Figure 5-4. Seasonal patterns of median daily stages in the Little Deschutes River at La Pine under unregulated and regulated flow conditions, 1983 through 2014, and unregulated and regulated daily stages at the same location under interim operations in 2015.

6.0 Literature Cited

Oregon Water Resources Department (OWRD) 2001. Upper and Middle Deschutes Basin Surface Water Distribution Model, Surface Water Open File Report # SW02-001 prepared by Jonathan LaMarche, September 30.

Oregon Water Resources Department (OWRD) 2016a. Daily flows and rating curve for Crescent Creek at Crescent Lake near Crescent, Oregon, Gage No. 14060000, September 30, 1983 to December 31, 2015, http://apps.wrd.state.or.us/apps/sw/hydro_near_real_time/display_hydro_graph.aspx?station_nbr=14060000.

Oregon Water Resources Department (OWRD) 2016b. Daily flows and rating curve for Little Deschutes River near La Pine, Oregon, Gage No. 14063000, September 30, 1983 to December 31, 2015, http://apps.wrd.state.or.us/apps/sw/hydro_near_real_time/display_hydro_graph.aspx?station_nbr=14063000.

United States Bureau of Reclamation (Reclamation) 2016. Daily storage and water surface elevations for CRE – Crescent Lake near Crescent, Oregon, September 30, 1983 to December 31, 2015, http://www.usbr.gov/pn-bin/arcread.pl?station=CRE.

United States Geological Survey (USGS) 1982a. Measurement and computation of streamflow: Volume 1. Measurement of stage and discharge, USGS Water Supply Paper 2175, Prepared by S.E. Rantz and others.

United States Geological Survey (USGS) 1982b. Measurement and computation of streamflow: Volume 2. Computation of discharge, USGS Water Supply Paper 2175, Prepared by S.E. Rantz and others.

United States Geological Survey (USGS) 2001. Ground-water hydrology of the Upper Deschutes Basin, Oregon, USGS Water-Resources Investigations Report 00–4162, Prepared by Marshall W. Gannett, Kenneth E. Lite, Jr., David S. Morgan, and Charles A. Collins.

United States Geological Survey (USGS) 2002a. Standards for the analysis and processing of surface-water data and information using electronic methods, USGS Water-Resources Investigations Report 01–4044, Prepared by V.B. Sauer.

United States Geological Survey (USGS), 2002b. Geological framework of the regional ground-water flow system in the Upper Deschutes Basin, Oregon, USGS Water Resources Investigations Report 02-4015, Prepared by Kenneth E. Lite, Jr. and Marshall W. Gannett.

United States Geological Survey (USGS), 2004. Simulation of regional ground-water flow in the Upper Deschutes Basin, Oregon, USGS Water Resources Investigations Report 03-4195, Prepared by Marshall 2. Gannett and Kenneth E. Lite.

United States Geological Survey (USGS) 2010a. Stage Measurement at gaging stations, USGS Techniques and Methods Book 3, Chapter A7, Prepared by Vernon B. Sauer and D. Phil Turnipseed.

United States Geological Survey (USGS) 2010b. Discharge measurements at gaging stations, USGS Techniques and Methods Book 3, Chapter A8, Prepared by D. Phil Turnipseed. and Vernon B. Sauer.

United States Geological Survey (USGS) 2016. Streamstats Version 3.0: OR, http://streamstatsags.cr.usgs.gov/v3_beta/viewer.htm?stabbr=OR